NISTIR 6507

The NIST Electronics and Electrical Engineering Laboratory and the Development of its Semiconductor Program -- A Presentation to the Standards Alumni Association

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(EEEL)

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EEEL's formal mission is to promote U.S. economic growth through improved competitiveness, by providing measurement capability of high economic impact focused primarily on the needs of U.S. electronics and electrical equipment industries. (Fig. 1)*

We do this by providing measurement research and services, principally in our five technical divisions. (Fig. 2) We cover in the Electricity Division the provision of the Nation's basic, primary electrical standards, and support for electronic instrumentation, the electrical utilities, video technologies and electronic product data exchange, and, cover in the other divisions, semiconductor electronics, radio-frequency and microwave and millimeter wave signals and interference, superconductors, magnetics, and optoelectronics. EEEL also has two offices. One, the Office of Law Enforcement Standards, provides technical soundness to tests of products used by law enforcement officers. The Office matrix manages laboratory work across NIST covering things from speed detectors to DNA tests. Obviously, EEEL never lacks exciting and unusual tasks. But I'm not going to say any more about that today. The other, the Office of Microelectronics Programs, I will talk about later. To give you a feeling for our size, our resources comprise a total budget of $ 46 M of which $ 30.7 M is Congressionally appropriated funds for Scientific and Technical Research and Services (STRS), and a staff of 322 supplemented by 79 guest scientists and research associates. (Fig. 3) Our resources have a profile in funding and professional staff generally characteristic of all the NIST Labs. But we are unique in providing over 40 percent of all NIST's calibration services, represented here by the $ 2.1 M in calibration fee income.

The needs addressed by EEEL are familiar ones in the fast moving world of electronics -- the

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* The identified figures exclude illustrative photographs associated with technical topics.

industry has outstripped the measurement tools available to control its materials and processes and evaluate its products. (Fig. 4) Our role, and our informal mission statement, is: to provide measurement tools that industry must have to provide and prove world leadership in performance and quality of its products.

The points I especially want to make about EEEL are these. (Fig. 5)

First, the primary clientele we serve is the electronics industry taken very broadly. It extends from the electrical utilities to lightwave communications, and includes the suppliers to this community, and it includes the users of their products and services. It ranges from the Fortune 500 companies to start-up companies. Our clientele also includes other Federal agencies, of course, who depend on our metrology services, and it extends to the academic world as well.

Second, we concentrate on metrology, which is the science of measurement as I'm sure this audience knows. Despite all the excitement about technology development since NBS became NIST, we have continued our focus on measurement research and services.

We have found this contribution to be unique, badly needed by our sophisticated industry, and to have a major impact on manufacturing productivity and quality, as well as on marketplace equity and efficiency, and even on innovation. (Fig. 6) Further, it leads spontaneously to spin-offs in generic technology that is of great value to our clientele: for example, some fifty companies have commercialized in hardware over 30 products of our metrology work along with some 10 software products. Indeed, as a result, even new companies have been formed in some cases; and business practices have changed. I'll give you some examples later.

There is a broad new recognition in industry of the significance of accurate physical standards, and of the processing and performance standards that depend on them. This comes about as industry is forced to meet conformity requirements in the international arena, and cost and quality requirements in its manufacturing plants.

The semiconductor industry has developed a new Roadmap which shows it must institute major metrology advances as it continues to shrink devices to nanometer scales; and remember a nanometer is only the length of a few atomic diameters, one ten-thousandth the diameter of a hair. The Roadmap has incredible measurement uncertainty requirements. So the Semiconductor Industry Association (or SIA) has just written the strongest statement of need for metrology I have ever seen an industry association produce. I will show it to you later. The optoelectronics industry published a new technology roadmap last year, and the original equipment manufacturing (or OEM) industry has been driven this year to a new intercompany collaboration to plan exploitation of advanced electronic and optoelectronic components as soon as they appear, before our foreign competitors do. A new draft roadmap to mesh with the semiconductor and optoelectronics roadmaps was disclosed last March.

All of these have been shown to require advances in measurements. So my third point (Fig. 7) is that in the face of this immense range of needs and our limited resources, we must choose and plan our projects very carefully; we do this by close interaction with the industry during the selection process, throughout the course of the research so that we receive continuous feedback on our progress, and finally by checking on our whole planning and research process by evaluating our actual impact with the assistance of our clients in industry.

To do all this, we have many ways of interacting with our clients to learn their needs, to deliver our products, and to see how well they are used.

For example, just in the last year we have sponsored or co-sponsored nine major workshops for this purpose and also to enhance our clients' own activities. (Fig. 8) These covered electromagnetic compatibility, video technology, instrument tests, semiconductors, and optoelectronics.

We've participated in the industry's roadmap planning activities and in key government-industry planning committees such as those of the Civilian Industrial Technology Committee of the National Science and Technology Council (this work actually stimulated the OEM collaboration); and we have interacted directly and personally with our clients in a number of ways, especially in discussions in their own labs where they'll tell us things they won't talk about in workshops and committees. (Fig. 9) Altogether, we've collaborated with or served in some substantial way over 2000 different organizations in recent years; and we've received a lot of useful guidance and feedback from them.

We use questionnaires and conduct field studies such as these (Fig. 10) to learn specifics of industrial requirements. Many of these studies involve visits to over 30 different companies and lengthy interviews with over 100 individuals. Some of the results end up in in-house working documents.

Some are in published studies like this one (Fig. 11) in which we have identified, and reviewed with industry, proposed plans for work needed in metrology. Incidentally, while we prepared this for our own in-house purposes, we have already received over 900 requests for copies because our clients have told us they actually find it useful for their own internal planning.

The results of all this end up in our Strategic Plan and in our selection of broad technical thrusts (Fig. 12) which cover the enabling technologies of semiconductors, magnetics, and superconductors; technologies covering the frequency ranges from those of the electric power networks to lightwave communications; the interference that all these technologies can produce; and the special topics of video technology and standards for electronics product data exchange. Perhaps most important of all are our research, development, and dissemination activities in support of the nation's primary electrical standards. The results of our surveys also guide our detailed project selection and our program plans which we publish each year. (Fig. 13)

Does all this work? There is lots of evidence that it does. We constantly inquire of our clients about their use of our work and collect anecdotes in trip reports and other ways. But perhaps more convincing are over a dozen formal studies that have shown it has paid off, and very handsomely.

(Fig. 14) For example, our earliest studies of our work in semiconductors were very encouraging and our more recent ones even more so. (Fig. 15) Our work in electromagnetic interference saved automotive manufacturers alone more than $ 16 M a year and, overall, resulted in a social rate of return on investment of 266 percent. Our optical fiber work yielded 423 percent; you'll hear some reasons why in a few minutes. And our research in support of our electric utilities power and energy calibrations gave a return of over 400 percent as a result of reduced time lost in disputes and in advances in metering technology, for example.

Our median value of social rate of return on investment is well over twice that found for private sector innovation shown at the top of the figure.

The economic experts that help us in these studies assure us that ours are conservative figures since they are typically based on just a single step in the economic commercialization process and do not include many downstream benefits which themselves are very significant.

So much for "how we work". Now let me give you some examples of our work, our activities, and their outcome.

Our measurement and calibration services provide the basis for all the electrical measurements made in the U.S. Some examples are the basic d-c voltage calibration service; microwave calibrations, provided by a unique six-port system developed at NIST; and antenna calibrations. In all these cases, our developments have provided the most accurate measurements in the world, but they go farther than that.

For example, we introduced the theory and methods that permit indoor, near-field scanned measurements of antennas to replace costly and unreliable outdoor measurements, and further, to allow diagnostics and adjustments to be made in phased array antennas during actual manufacture. As a result some 15 U.S. companies have installed 40 near-field calibration facilities. One company has reported a $ 35 M saving and another a reduction in testing time from a month to 12 hours using such facilities. And during the “Desert Storm” warfare, we provided almost an overnight solution in a crisis situation where we could respond best and fastest.

Now our microwave program has expanded to cover new work on properties of materials and radar cross-section standards, and most importantly it has led to the development of a successful consortium for microwave integrated circuit measurements to be made directly on the wafer during manufacture. We've introduced new measurement methods based on transmission line test structures formed directly on the semiconductor wafers, and disclosed large errors (> 30% in some cases) in traditional industrial measurements that frustrate design and reduce productivity. Our results have been incorporated in commercial test instruments and adopted by major companies. Forgive me, but I have to brag a bit about our staff and say that eminent people in the field have praised this work, calling it the greatest advance in microwave circuit theory in 50 years.

To our surprise, we have learned that even our most basic measurement research has to advance rapidly to keep abreast and ahead of our very fast moving industry's practical needs, so we can facilitate its product development and marketing. Let me give you some examples.

As one result of our research in superconductivity, we discovered how to make operable a large array of Josephson junctions that now serves as the national standard for the volt, not only in this country but in many others as well. And our development of a still larger array, with over 20,000 junctions providing a ten-volt output, turned out to be essential for Hewlett-Packard to be able to introduce what was, at that time, the world's most advanced and accurate multimeter. H-P now uses the array for manufacturing and quality control, and small companies have commercialized the NIST instrumentation that operates the arrays. So, now the best physical standard for voltage in the world is at work every day in manufacturing plants.

As another example, with an industry partner we have just developed a solid-state ac-dc thermal transfer device to provide an ac voltage standard replacing the hand-made "vacuum tube-type" standard used for decades in most national standards labs. It is made using semiconductor technology so it is reliable and relatively cheap and potentially installable directly in commercial instruments giving them standards lab accuracy.

These last two examples show another strength and a new challenge in EEEL: as we find new ways to bring national laboratory accuracy close to or in commercial instruments, we face the challenge of how to keep ahead of our clients' needs! At the moment we are doing research on quantum Hall devices, single-electron tunneling, and new applications of Josephson junctions as potential leaps ahead in measurement accuracy.

I will give you just a few more examples to show the breadth of coverage needed in our work.

Over the years our work with the optical fiber industry has provided the technical basis for over two dozen of the Telecommunications Industry Association's (TIA) standards, leading the President of the TIA to say, "Without the NIST assistance and leadership, the U.S. fiber optics industry would not be in the competitive position it is today." (Fig. 16) More recently, U.S. manufacturers developed a concern about their ability to make optical fibers with the circular cross section with sub-micrometer tolerances needed for connectorization and to avoid large signal losses in multiple connections. Responding to a TIA request, we provided improved measurement methods and a standard reference material (SRM) that solved their problem and now all the fiber-drawing towers of the major U.S. manufacturers use these SRM's for production control.

Software based electronic instruments, typically using analog to digital converters, require thousands of measurements for evaluation, and demand a new test strategy for cost effective use in manufacturing and evaluation. We've developed the theory that permits a greatly reduced data sample to give accuracy practically equivalent to a full test. For example, the 8192 measurements for a 13-bit converter can be replaced by only 64 measurements, reducing test time 90 percent, to 2 seconds. A major manufacturer of automatic test equipment for microelectronics has incorporated our strategy in its products, and several integrated circuit manufacturers have adopted it for production-line application.

In our most recent work in magnetics, EEEL developed measurement methods to study nanoscale friction forces on recording disks in a collaboration with a major manufacturer of computer disk drives. The forces arise from sticky projections 20 or 30 nm high on a hard disk memory which interfere with reduced flying-height of the magnetic-signal reading heads needed for increased storage density. We adapted atomic force microscopy to measure the lateral forces involved. Our researcher in this work has just completed six-months as a NIST Industry Fellow at the company, helping to establish and operate a magnetic-force microscopy lab there. He also learned from first-hand experience in a business environment how best we can serve our clients. EEEL has had several of these Industry Fellows in the field already, experimenting with this new NIST Fellowship Program.

Turning to a different field, micro-electro-mechanical systems, or MEMS. These are microscopic structures including accelerometers (such as the ones that control the air bags in your car), pressure gauges, and analytical instruments made using semiconductor device construction techniques. We've fostered a new inexpensive way to make such devices using semiconductor foundry services as described in a cover-page article about one of our devices, and EEEL is extending its semiconductor test-structure experience to provide MEMS designers and manufacturers with methods to determine micro-mechanical properties of MEMS devices and their components.

As a final example of breadth, we have just completed establishment of a video-display measurement laboratory to help industry develop objective standards for visual quality of displays, which currently are not available, and we have begun cooperative work with several other organizations.

The bottom line to all this is that through its measurement research and services, EEEL really makes a difference to the electronics industry: in improving productivity and profitability as shown by our return on investment data, in stimulating new products and new company start-ups, in changing important industry practices, and in influencing technical and policy actions. (Fig. 17)

You'll find more details of our recent work in our publication entitled "Electronics and Electrical Engineering Laboratory 1994 Technical Accomplishments" (NISTIR 5551). (Fig. 18) This describes our laboratory work and its results for 1994, in a very readable form, and there are copies here for all of you.

Now I want to tell you about the NIST semiconductor metrology program and a few of the stories associated with its history that we don't tell very often: stories of the not-so-sophisticated early semiconductor industry, of the several times the program faced sudden bankruptcy, and of some of its current technical work and recognition.

Shortly after the transistor was invented, the proximity fuze program at NIST developed a strong transistor program in the old Tube Laboratory but when the Harry Diamond Lab was formed and spun off, the transistor program went with it, leaving NIST without work in an area that looked pretty important even 40 years ago.

So in 1955 NIST found $ 30 k to start a program of its own and divided it among three Sections in the Electricity and Electronics Division. (Fig. 19)

Ten thousand dollars went to Franklin Montgomery to be used to provide transistor-based instrumentation services, ten thousand went to Gus Shapiro's Section and ten thousand to Charlie Marsden's Electron Tube Lab. Montgomery's transistor work merged with the general instrumentation service and disappeared when that service did. Shapiro's was used to start some reliability studies that became focused on the Navy's Polaris and Poseidon submarine missile programs, did some very valuable work for the Navy, and then that disappeared when Gus' Section did.

Charlie Marsden gave his $10 k to me. I was working on microwave gas discharge tubes then, so my first act was to buy Shockley's book on transistors and sequester myself with it until it was well absorbed.

As I looked around to see what the Tube Lab could do that was unique, since nearly every technical agency in the Washington area had transistor work underway, I soon found that these agencies needed help in characterizing their devices and materials; there were no universally available or accepted measurement methods and only limited commercial test sets. So that was a great opportunity. A focus on measurements was both unique and especially appropriate to NIST. With some of the people in the microwave tube group, Bill Keery and Marvin Phillips, at the start, we began to develop some competence and increase our resources with some other agency projects. After we felt more confident, I went first to ASTM and then to the Electronic Industries Association (EIA) to see if there was a need by the industry for NIST services and if so what it was.

There was an immediate and very positive and surprising response. For example in ASTM, leading companies were actually arguing with each other for the opportunity to tell me what, and how badly, help was needed, and each wanted us to do it their way. In each association there were measurements identified which were important both to manufacturing processes and to product specifications and in which there were great discrepancies. The member companies themselves had not found any acceptable ways to resolve them.

From each organization we picked one problem, resistivity and second breakdown, respectively, that matched our mission and competence. Both were very successfully addressed with results which were applied industry-wide. I'll describe one of these in some detail because these first projects set the tone for the whole future of the program.

The problem that ASTM members identified was the measurement of silicon resistivity; resistivity is the most important property of semiconductors for device design and manufacturing. (Fig. 20) Discrepancies in measurements within and between companies were many <u>times</u> the needed uncertainty either for manufacturing control or material purchases. Initially industry advised us that only a destructive two-probe method could provide the precision required. But I thought I'd better look further before we started to work, and this was the first of numerous experiences that taught us that what people in committees and workshops thought and said didn't always reflect what was really happening in their labs or plants. (Fig. 21)

Because we at NIST were not a contractor or a regulator or a competitor, we were able to visit companies all over the country, and learn some of the real causes of the discrepancies. Finally, in our lab we found, to the industry's surprise and delight, that we could provide a non-destructive four-probe method using a commercial instrument in a carefully defined way that gave the desired precision. (Some of the most important research leading to this was done by Lydon Swartzendruber who is now in Materials Science and Engineering Laboratory). With ASTM we tried it out in inter-lab tests with industry and found it was practical and better by an order of magnitude than existing practice, and it could be used in the manufacturing area as well as in a standards lab. These results became universally used, provided the basis for five industrial standards, and led to our producing several standard reference materials which are still being bought by the industry to calibrate their measurement instruments, and are being supplemented by new versions to meet new needs. That's the story as we usually tell it, but what we learned on our trips really opened our eyes to what life was really like in this supposedly sophisticated industry.

The companies needed a 3% control on resistivity at worst. But a silicon supplier told me they had to add a 15% corection to their measurement when they delivered it to one building at one of the then biggest transistor companies and subtract 10% or so at another building of the same company. Silicon resistivity is very temperature sensitive. A small supplier lost its reputation and failed because of poor quality control -- the manager wouldn't authorize purchase even of an aquarium heater to maintain constant temperature; and a big company carefully measured the temperature variation of p-type silicon, then made one measurement on n-type as a check, found it the same as p-type and so they adopted the results. We found that that one point was where the two very different curves just happened to cross. In another plant, we found a radio-frequency induction heater operating on the other side of a wall from the resistivity test set. Every time it was turned on, the four probes of the test set acted like diode rectifiers and spoiled the measurement accuracy. And the industry's correction factors for the 4-point probe were seriously wrong, and so on and on.

Back when the first major phase of the work was completed, we did a benefit-cost study, the first we had ever done. (Fig. 22) The industry helped us define and conduct the study and reviewed it on completion for their approval. It showed economic benefits estimated by industry at over $30 million dollars (over 100 times the cost of the work) in marketplace transactions alone, and perhaps as much as ten times this amount in manufacturing economies. (There is an interesting report that tells about all this.)

In the years that followed, new benefits accrued. Even during recent years, more than 180 different companies have purchased NIST resistivity SRMs. A vice president of a corporation which had a substantial share of the process control systems market said "the availability of resistivity SRMs was a significant factor in successfully developing and selling the $50 million installed base of these systems." The president of another company has said that their spreading resistance systems are dependent on these SRMs.

I mentioned that our other initial project addressed the property and potential failure mechanism, second breakdown, that for a long time had been a costly problem in power systems. This project led to improved understanding and methods for characterizing the property, principally developed by Harry Schafft, that were adopted throughout the industry for its power device specifications. A highlight of the course of this work was Harry's and my meeting in my office with Bill Shockley who had decided to resolve this plaguing topic once and for all and had come to tell us about his new theory. We nervous novices had to figure out how to tell the great Shockley we thought he was wrong. He really was a great man; he listened with an open mind as Harry described our data and then Shockley proceeded to tell us he must be wrong, and started on the spot to introduce our data into a new theory. But it was Harry's work that satisfied industry for many years and even resolved a problem in the main engine control delaying launch of a space shuttle a few years ago.

So a point I want to make is that our work from the beginning has been guided by industry needs for measurement improvement: by market pull, not by our technology push. (Fig. 23)

Requests for our services grew as we became better known. We developed a joint program with other Federal agencies and they provided funding to supplement our small internal support. (Fig. 24) During this period, we looked for measurement needs the industry considered of top priority, and matched them to the needs of the other agencies. As many as ten agencies at a time subscribed to the overall program, and each felt it was receiving specific mission benefits. In addition to our usual publications, we issued a combined quarterly progress report which not only went to all the agencies but was so highly prized by industry that we had ultimately a mailing list for these reports of about 2000.

This other-agency cooperation really leveraged our capability. (Fig. 25) But then disaster loomed. The Mansfield Act made it illegal for Defense agencies to fund generic technologies and we stood to lose 80% of our funding almost overnight. Since I had the primary responsibility for funding as well as managing this program, I was about to have apoplexy. By a stroke of good luck for us, it turned out that just at this time, in 1973, DoD realized it was having great difficulty getting integrated circuits with performance and reliability it needed. (Fig. 26) On DoD's behalf, ARPA asked us to undertake a multi-year, multi-million dollar program to help out. Martin Stickley, ARPA's Director of Materials Research, said he did this on the basis of our track record and effective delivery. I had dreamed up a cute acronym ARPA/IC/NBS to stand for Advances in Reliability and Productivity and Automation of Integrated Circuits at NBS; in a talk to industry Martin defined NBS differently, he said that, knowing NBS, the acronym really stood for Advances in Reliability and Productivity and Automation of Integrated Circuits with No B... S... .

Until this time, all our research had been conducted in house. This program called for the addition of external contracting with universities and private companies, which we learned to do. We also learned how hard it was to get other organizations to do measurement research that led to the necessary validated precision in the results, even when they were provided funds to do it; this was <u>not</u> their preferred mission. We learned also that achieving these results in contracts took a great deal of technical effort on our own experts' part and led us to believe it was better to do such work in our own labs. Nevertheless, six years, 30 contracts, 240 reports and papers, and $11 million later the work was completed. A major share of the credit for pulling this off so well goes to Murray Bullis who now has his own consulting business. I should say that Al Sher and Joe Coleman were important partners in those days, also.

At the conclusion of the work, the Director of ARPA was delighted. (Fig. 27) He wrote to the Secretary of Commerce, said the program had met its objectives; and its results had been put to good use by industry. He said dramatic improvements had occurred in performance and reliability of devices for DoD use; so that several Defense Department programs had each saved many millions of dollars. For example, it was during this period that we completed the major part of our studies of ultrasonic wire bonding of integrated circuits, the connections between the silicon chip and the outside world. Our work had arisen some years earlier (supported initially by the Defense Nuclear Agency) from a very serious missile-program problem, where rare but critical and unpredictable wire bond failures were a major system reliability problem. We knew nothing about bonding. We had torn George Harman away from his pet project in a totally different field to start this and he was given the best equipment off the dedicated military fabrication lines to try to make bonds to study the test methods. But George couldn't make good bonds routinely, and he found out why others couldn't either. He found the meter readings and controls on bonding machines had no relation to the tool's actual operation; lights on the bonders helped the operators see, but heated the ultrasonic transducers and moved the bonder out of specs; the bonders were so sensitive to vibration that on the commercial lines vibrations due to elevators in the building or to delivery of gas tanks led to unreliable bonds but nobody knew it, and so on and on.

Incidentally, at the start, George and Harry had done a country-wide on-site survey of practices and problems in bonding. They found that most companies had the same problems but thought they were alone in having them so they hid their problems and didn't talk to each other to solve them. With some new information to fill gaps in the theoretical interpretation of the "pull test" the extensive report of this trip, in a non-proprietary form, became a valuable stand-alone contribution, and was even used in university courses.

In our lab, George's work and leadership established new metallurgical understanding, and new procedures that led to radical changes in design of commercially available equipment and even new equipment; it increased productivity in high reliability circuit manufacture by as much as 35 <u>times</u>, and made possible the large military hybrid circuits which need over 500 wire bonds each. As noted in the ARPA Director's letter, in <u>two</u> major military programs which employed the new bonding procedures, no field failure of devices due to faulty bonds occurred, where bonding was previously a major cause of failure. George has gone on to become a treasured consultant to the biggest companies in industry to this day, receiving top honors and a Fellowship in IEEE, every award the International Society for Hybrid Microcircuits offers including its Presidency, as well as DoC's Gold and Silver Medals and NIST's Condon Award and he is now a NIST Fellow.

At about this time NIST was trying to learn how to determine the impact of its work. (Fig. 28) It picked the semiconductor program because it had the best documentation and list of contacts to start with and asked the Charles River Associates (CRA) to conduct the study. Industry told CRA that the benefits received from the use of the NIST results included improved product reliability, production yields, ability to meet customer specifications, product features, as well as cost reductions, and even new directions of company research.

The report concluded that "the overall industry productivity level was approximately one percent higher for the years 1973 to 1977 [which were covered by the studies] than it would have been had the technical information acquired from NBS not been available."

Later, comparing this with industry data, it was found this meant that NIST's tiny program had provided four percent of the total industry productivity increase during the period.

The CRA study also showed that the social rate of return on investment in the NIST work was considerably greater than that for typical industrial innovation as you saw earlier.

The ARPA program was so successful it was extended well beyond its planned period, and when it was to be phased out the Services' R&D groups were told to pick it up. The Services had other things to do with their money, however. So for the second time disaster loomed. The program had grown to a staff of 60 with a total budget of about $6 M. We were receiving calls for some aspect of the program each year by several thousand representatives of over 500 business organizations, agencies, or universities, so loss of the program was not a minor problem.

But again luck was with us. We had tried nearly every year for many years to get internal funding for the program without success and just in time we "won the lottery" again and a major budget initiative was successful. (Fig. 29) We had been living on only 20% internal and 80% external funds. In 1981 the budget increase reversed this rate and made us really solvent. But, doom and gloom, it seemed not for long.

The Office of Management and Budget (OMB) was seeking by every means to reduce government costs and it questioned why the obviously high-tech semiconductor industry needed any research assistance, and especially why from NIST. This was an interesting question because NBS was originally established to provide metrology to high technology industries. In 1901, the newly developing electric power industry was a primary client of NBS and indeed a key stimulus to the formation of NBS. High-tech industries "push the envelope" of measurement technology -- it is precisely these industries which most need the measurement infrastructure NIST provides. OMB didn't care; it wanted to cut the budget. I was desperate and politically naive, so I called George Heilmeier. George was Vice President for Research at Texas Instruments, but he had been a very successful Director of ARPA part of the time we worked for ARPA, had been on our Assessment Panel, and was one of our best friends and supporters. To shorten a long and fascinating story, the problem was turned over to the Semiconductor Industry Association (SIA).

SIA appointed a high-level group including a vice president at IBM, and other high-level people from DEC, Rockwell, and Signetics (who actually each sent technical experts to act for them) to review the NIST work and report on its value to the industry. (Fig. 30) After they did, they were so supportive that the SIA President wrote to the Director of OMB and the Secretary of Commerce, saying that the program was essential, that it was in the national interest to support it since the issues extended beyond the semiconductor industry because semiconductors are the basis of world leadership in computers and electronics, and that the program must be continued. It worked, and once again the program survived.

But the semiconductor industry itself almost did not. You probably know from TV and the newspapers that it lost market share because of Japanese devices with higher reliability and lower cost. This was a situation we had predicted because of our inside view of our industry's quality control principles and its customers' needs. But then, in desperation, this individualistic industry turned itself around by actually collaborating on generic technologies and really focusing on quality and productivity. And this has led to the SIA reaffirming its earlier statement about the importance of metrology and NIST's role in the three reports to the President and Congress from 1989 to 1992 from the National Advisory Committee on Semiconductors (Figs. 31, 32), in its subsequent Roadmaps and in a particularly significant position paper written in 1995 that I'll show you later. All this, of course, was going on as the semiconductor industry continues to push the technology to smaller and smaller feature sizes with more demanding design and manufacturing processes, always with cost and quality in the forefront.

In 1993 the SIA released its report on a landmark semiconductor technology workshop, laying out a roadmap for future generations of silicon digital integrated circuits. (Fig. 33) The report identified metrology as an essential and pervasive competence. It also recognized NIST as the only organization systematically developing the broad range of measurements needed for semiconductor processing.

To respond to the incredible range of measurement expertise needed for this industry, several years ago we broadened our semiconductor program to a NIST-wide matrix managed activity that involves all but one of the NIST Labs. (Fig. 34) EEEL manages the Program but nearly 60% of its funds in 1995 went to other NIST Labs. On the recommendation of the SIA, as one of its highest priorities, this program has now formally become the National Semiconductor Metrology Program, focused on the national semiconductor roadmap and officially announced to the press by Secretary Brown last March, with a goal of achieving a $25 M operating level by 1997. The current program is described in a publication, the NSMP Project Portfolio, FY 1995. Today this is a $10 M program which stands in addition to another $ 3 M in EEEL devoted to semiconductor topics such as compound semiconductors and power devices not on the silicon Roadmap.

Sounds like a wonderful story doesn't it?

And now what has happened? Shades of the OMB story; now the Congress is relentlessly cutting the budget and our future growth is again in doubt. So it's a great story, but it's not over yet. Keep tuned.

Now for a few minutes, let's forget budgets and politics and see what kind of real, technical accomplishments we've made.

Today there are over 30 tasks in the NSMP and the Semiconductor Electronics Division, but I can only mention a few.

Our work on photomask linewidths led to the reduction of intercompany measurement discrepancies by an order of magnitude, stimulated the production of new commercial instrumentation, extended the range of use of optical microscopes, and provided techniques and calibration standards in the form of SRMs, shown in the slide costing $ 5,000 each, that have been adopted industry wide. See those little spots at the end of each line? They look like this (in this next slide), with lines down to

0.5 mm.

Three of the top companies in the industry, for example, ceased world-wide use of their internal standards and adopted those of NIST.

One study of the benefits of this work estimated a $30 M annual saving to the photomask producers alone.

We have developed the world's most accurate ellipsometer to develop and support the issuance of SRMs for measurement of insulating silicon dioxide layer thickness and control of critical gate oxides covering the range from about 10 to 200 nm. At a price of about $1300 each, the first batch was a sellout before it was even issued. Analytical computer programs, we developed for this research, are in use by three companies for product commercialization.

And in 1994, a year ahead of the industry schedule, we demonstrated that industry can achieve repeatability of 0.3 nm or better which is a 1995 semiconductor industry Roadmap requirement.

Integrated circuit test structures are now universally used. They are microscopic measurement devices formed right on the wafer during manufacture. They can be electrically probed to measure properties of materials, quality of processing steps, device operation, and even mechanical properties. NIST (especially Martin Buehler, who is now at the Jet Propulsion Laboratory) stimulated the first marketplace use of these test structures and since then has contributed a lot to their breadth of application and reliability in process-line use.

In the packaging area, George Harman literally "wrote the book," a best seller, on wire bonding. Most of the industry standards of JEDEC and SEMI for thermal properties of devices and packages are based on work led by Frank Oettinger.

As part of our metrology research, development of reliable mathematical models is essential. One recent example includes modeling of the failure mechanism, electromigration, which results from such high current densities that the electron flow moves material and breaks the connection. Our electromigration results have been used by at least 14 companies, including the leading computer and semiconductor manufacturers, and an external study has estimated industrial savings already of $26 M in return for the $1.6 M spent on our project. The results are the basis for three industrial standards, and one company supplies test stations and a library of standard structures based on NIST's recommendations.

In another example, through work with Analogy, Inc., and Alliance Technologies, Inc., our models to simulate advanced power devices called IGBTs have been incorporated in commercially available software, and are in use by a variety of companies including Motorola and Ford Motor Company. We need the models for our measurement work, but these models have been used by Motorola to propose a new power transistor to Ford, negotiate suitable device characteristics and try them out in Ford's ignition system simulator without ever actually making a device. With Ford's contract in hand, Motorola started production on the brand new product. This is a whole new way of doing business. Now you can buy a Ford with these devices in them.

Finally, I can't resist giving one example that shows that despite all of our careful planning and priority setting; things do turn up that suddenly change our plans. You may remember that a few years ago the only satellite providing our national weather service was threatening to fail and was seriously in need of replacement, but the replacement was in such trouble that it had even drawn extremely strong Congressional criticism. Reliability of sensors in the new GOES (geostationary operational environmental satellite) satellite, which were based on unique infrared detectors, were a critical factor in a launch decision. On NOAA's request for emergency help, EEEL put together a team that showed first that the sensors were almost certainly defective for a variety of reasons, and so the satellite launch was delayed. Then the team provided, in a very short, crash program, new, basic magnetotransport measurement methods to monitor electron densities that indicated the basic device functionality, plus test structures for monitoring device parameters after each process step, and, finally, improved bonding and packaging procedures. These allowed the manufacturers to improve the yield and reliability of the GOES devices, and permitted a successful launch and operation of the new weather satellite, all within a critical deadline. The results turned out to have similar quality benefits to a broad range of infrared sensors used in many satellite systems, so they actually provided a step ahead for this whole area.

I have only scratched the surface with these examples. But I want to close by saying that the most important conclusion to draw from this story is that metrology for semiconductors has really arrived as a national priority and NIST has a key role in it. I think it is pretty clear why this is so.

Semiconductors underlie almost every activity in our modern society, from consumer products, banking, business, and manufacturing, all the way to transportation, as this slide shows impressively. (Fig. 35)

As semiconductor technology advances to provide smaller and more convenient and more powerful systems, and smaller and more dense circuits, the ability to control device understanding and manufacture adequately demands incredible advances in measurement tools. (Fig. 36)

And, as the SIA points out in this very strong statement I promised to show you, metrology is a key enabler in every step in semiconductor design and manufacture. "Without satisfactory metrology the industry will not be able to follow the Roadmap and will cease to be competitive..." (Fig. 37)

It is nice to know that the semiconductor industry looks to NIST as a unique source of help in maintaining our national competitiveness.

This is a feeling that seems to be shared by the rest of the electronics industry as it draws on our whole EEEL program, as I hope I have shown you.

Thank you.

EEEL Mission

To promote U.S. economic growth through improved competitiveness, by providing measurement capability of high economic impact focused primarily on the needs of U.S. electronics and electrical equipment industries.

Figure 1

EEEL Measurement Research and Services

Electricity Division

- **Basic standards, conducted signals, energy, video, and product data exchange**

Semiconductor Electronics Division

- **Semiconductor electronics**

Electromagnetic Fields Division

- **Radio-frequency signals and interference**

Electromagnetic Technology Division

- **Superconductors and magnetics**

Optoelectronics Division

- **Optoelectronic materials, components, and manufacturing**

Figure 2

EEEL Resources

Operating Budget	**$46.0M**	**100%**
STRS	30.7	67
ATP	2.1	5
Calibration	2.1	4
Other Agency	11.1	24
Total Staff*	**322**	**100%**
Permanent Staff	283	88
Professional	215	67
Ph.D.	116	36

*Excludes 79 Guest Scientists and Research Associates

Figure 3

Needs Addressed:

Electronics industry has outstripped available measurement tools to control its materials and processes and evaluate its products.

EEEL's Role:

To provide measurement tools industry must have to provide and prove world leadership in performance and quality of its products.

Figure 4

EEL

- Supports electronics industry defined broadly

- Concentrates on metrology and associated technology

- Emphasizes planning to maximize impact

Figure 5

EEEL

EEEL concentrates on metrology and associated technology:

- Unique, essential combination
- Major, broad-ranging benefits

Accuracy of physical standards increasing in importance:

- For conformity in international arena
- For productivity and quality in manufacturing

Examples evident in new roadmaps:

- Semiconductor industry
- Optoelectronics industry
- OEM industry

Figure 6

EEEL

- Supports electronics industry defined broadly

- Concentrates on metrology and associated technology

- Emphasizes planning to maximize impact

Figure 7

Improved Identification of Client Needs

Workshops in past year to identify specific needs:

- EMI-EMC
- Advanced video in NII
- Testing strategies of analog and mixed signal products
- Semiconductor characterization
- VLSI packaging
- Compound semiconductor roadmap initiation
- Characterization of ultra-shallow doping profiles in semiconductors
- JTEC optoelectronics
- Multilaboratory strategic planning workshop in photonics

Figure 8

Improved Identification of Client Needs

Participation in development of major industry roadmaps

- OIDA
- SIA

Participation in key government-industry committees

- Electronics Subcommittee and NEMI, Electronic Materials Working Group, under CIT/NSTC
- Joint Management Committee for U.S.-Japan Joint Optoelectronics Project
- JTEC Panel for evaluation of U.S. and Japan optoelectronics industries
- SIA Roadmap coordinating committee

Other client interactions

- 467 visits, 274 external talks, and 974 external consultations by staff in 1994; participants in 58 standards committees
- 176 cooperative projects with U.S. industry, including 94 active CRADAs, 4 consortia and 8 supporting projects for ATP

Figure 9

Examples of Special Planning Studies

- Silicon Resistivity
- Wire Bonding
- Photomask Linewidth
- Magnetics Calibration
- Magnetics Program
- Calibration services policy
- Dielectric Materials
- Low-Frequency electronics
- Lightwave metrology
- Microwave metrology
- Natn'l Laboratories calibration service benchmarking
- Advanced semiconductor metrology
- Lasers
- Optical fiber metrology
- Optical fiber sensors
- Electromagnetic compatibility
- Video
- Strategic planning studies
- Fields and interference metrology

Figure 10

NISTIR 4583

MEASUREMENTS FOR COMPETITIVENESS IN ELECTRONICS

First Edition

Prepared by the Electronics
and Electrical Engineering
Laboratory

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and
Technology
Electronics and Electrical Engineering
Laboratory

April 1993

NIST

Figure 11

EEEL's Technical Thrusts

- Semiconductors
- Magnetics
- Superconductors
- Power Networks
- Low Frequency Electronics
- Microwaves
- Lightwaves
- Electromagnetic Compatibility
- Video
- Electronic Data Exchange
- National Electrical Standards

Figure 12

NISTIR 5563

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1995 PROGRAM PLAN

Supporting Technology for U.S. Competitiveness in Electronics

Electronics and Electrical Engineering Laboratory

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory

January 1995

NIST

Figure 13

Examples of Special Impact Evaluations

- Silicon Resistivity, ‘67
- Wire Bonding, ‘72
- Semiconductor program impact on DOD contractors, ‘77
- Early semiconductor program, ‘82
- Photomask linewidth, ‘82
- Antennas, fiber optics, ‘90
- Semiconductors, fiber optics, ‘90
- Electromagnetic compatiblity / interference, ‘91
- Fiber optics, ‘92
- Electromigration, ‘92
- Superconductivity, ‘93
- Power and energy calibrations, ‘95

Figure 14

Formal Impact Studies

Social Rates of Return from Technology Investments

- **Typical industrial innovation: 56 to 99%**
  (Mansfield et al 1977: Tewksbury et al 1980; median percentage)
- NIST semiconductor work (3 areas): **63 to 181%**
  (Charles River Associates 1981)
- NIST electromigration work: **117%**
  (Link 1991)
- NIST EM interference work: **266%**
  (Link 1991)
- NIST optical fiber work: **423%**
  (Link 1991)
- NIST electrical power & energy calibration services: **428%**
  (Link 1995)

Figure 15

"Without the NIST assistance and leadership, the U.S. fiber optics industry would not be in the competitive position it is today."

A.R.Frischkorn,Jr.
President
Telecommunications Industry Association

Figure 16

EEEL Makes a Difference

Through measurement research and services, EEEL:

- Improves productivity and profitability
  - Return on investment data
- Stimulates new product commercialization
  - Over 40 hardware and software examples
- Stimulates new company start-up
  - Seven in recent years
- Changes in industry practices
  - Antennas, photomasks, voltage standards
- Influences technical and policy actions
  - Semiconductor / optical fiber round-robins and roadmaps...

Figure 17

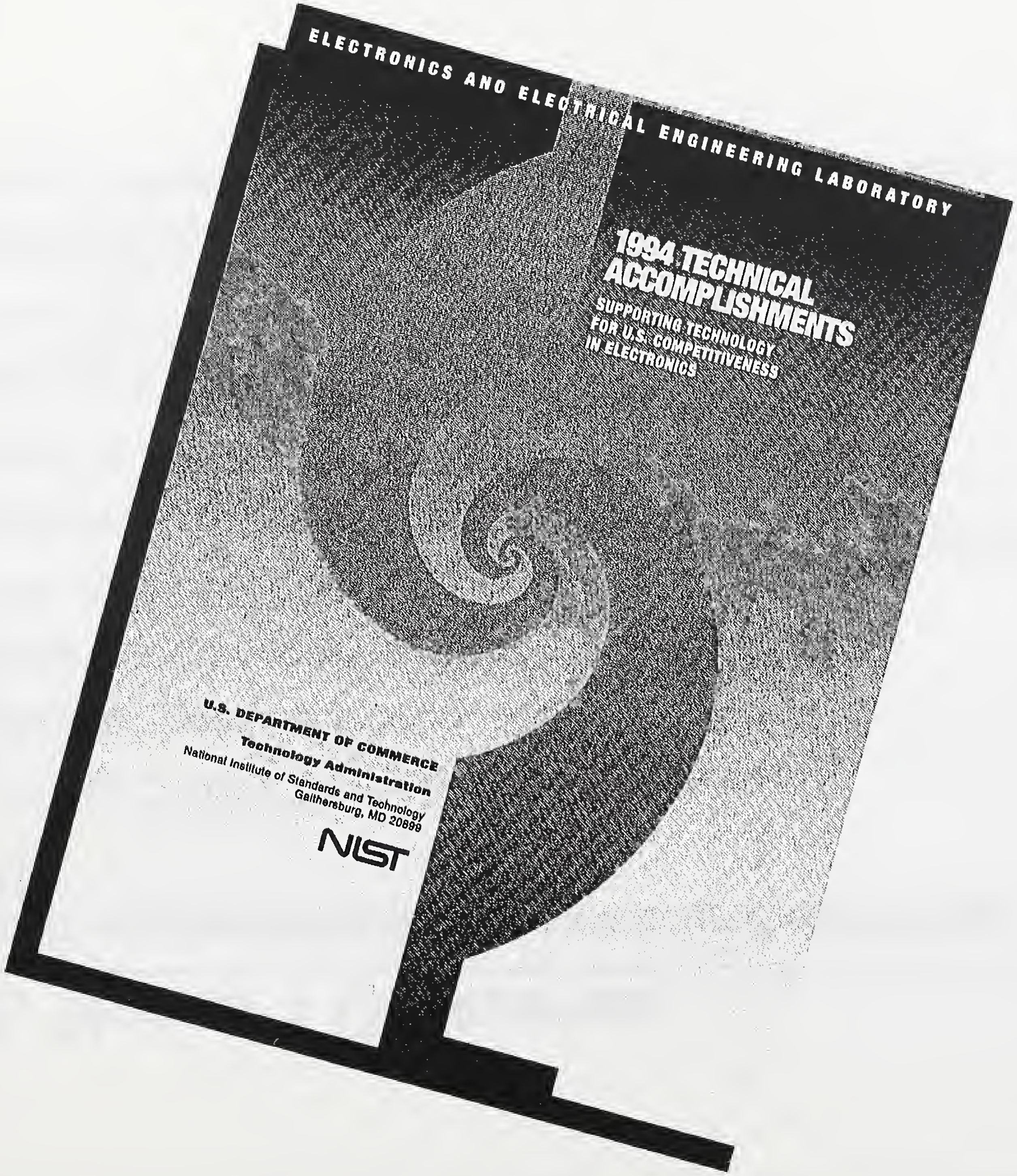

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY
1994 TECHNICAL ACCOMPLISHMENTS
SUPPORTING TECHNOLOGY FOR U.S. COMPETITIVENESS IN ELECTRONICS
U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Gaithersburg, MD 20899
NIST

Figure 18

In the beginning

- Started in late fifties
- First formal step: visits to ASTM and EIA
- Strong need identified
- Selection made:
  - high industry priority
  - match to NIST mission
  - successfully addressed
- Set tone for the program's future

Figure 19

Example: Silicon Resistivity

- Key to design and manufacturing
- Unacceptable measurement discrepancies in industrial practice
- Solution exceeded industry's expectations

Figure 20

Example: Silicon Resistivity (cont'd)

- Field study to guide technical work
- Non-destructive, practical method resulted
- Precision improved over 10 times
- Basis for 5 industrial standards
- Led to standard reference materials (SRMs)
- Still in use

Figure 21

Example: Silicon Resistivity (cont'd)

- Benefit cost study conducted with industry
  - over $30 M saved in marketplace
  - over 100 times cost of project
  - benefit to manufacturing much greater
- Later, additional major benefits reported

Figure 22

A Key Point (1)

From the beginning, the program has been guided by industrial needs.

Figure 23

The Joint-Program Era

- Industry needs matched to Federal agency mission needs and funding
- Ten participating agencies in a single coordinated program
- Widespread benefits

Figure 24

A Key Point (2)

Cooperation with other Federal agencies leveraged our ability to assist industry.

Figure 25

The ARPA (DARPA) Era

- The ARPA/IC/NBS program began in 1973
  - Selected NBS on basis of track record
- Comprised in-house research and contract management
- Six-year program
- Hundreds of benefiting organizations

Figure 26

The ARPA (DARPA) Era (cont'd)

- DARPA Director reported major benefits
  - for industrial control of materials, processing, devices,
  - through significant improvements in performance and reliability of devices for DoD
  - in millions of dollars saved, and
  - in major productivity and reliability and new product advances in wire bonding example.
- Recommended expanded internal DoC support
  - for benefit of national economy

Figure 27

An Impact Analysis

- Conducted by Charles River Associates
- Nature of benefits to industry identified
- Found overall industry productivity level was approximately one percent higher for the five years studied due to NIST output (four percent of total productivity increase for the period)
- Return on investment substantially higher than for typical industrial innovation.

Figure 28

Good News and Bad News

- New funds in FY-81 ended the traditional dependence on external sources for 80% of resources.
- But an economy drive led OMB to attempt to end the program.
- OMB's question: "Why NIST?"

Figure 29

SIA Response

- Reviewed NIST program
- Found it essential to the semiconductor industry
    - and of broader national interest
- Recommended continuation

Figure 30

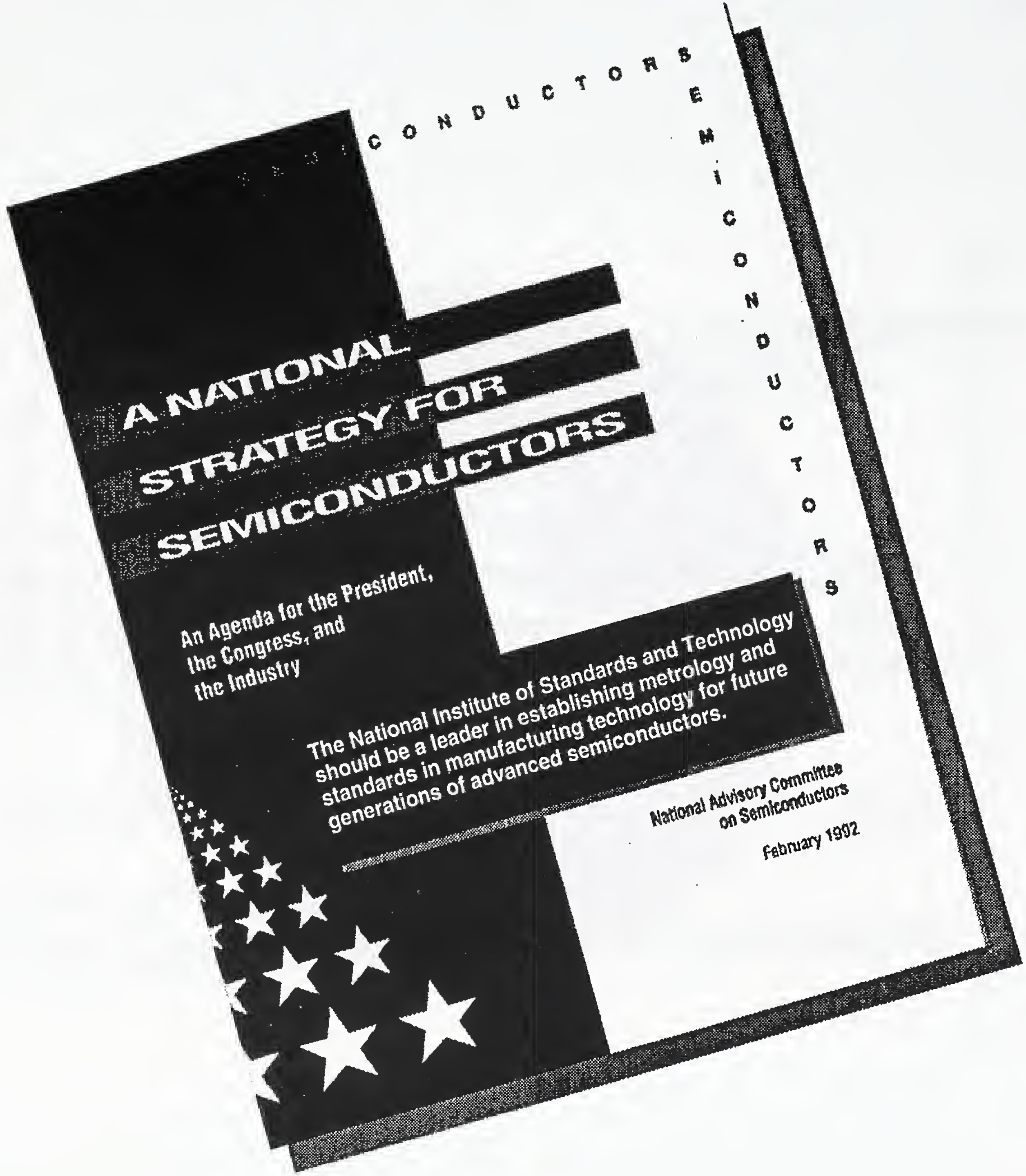

CONDUCTORS
SEMICONDUCTORS
A NATIONAL
STRATEGY FOR
SEMICONDUCTORS
An Agenda for the President,
the Congress, and
the Industry
The National Institute of Standards and Technology
should be a leader in establishing metrology and
standards in manufacturing technology for future
generations of advanced semiconductors.
National Advisory Committee
on Semiconductors
February 1992

Figure 31

Enable U.S. Industry to Achieve a Competitive Technology Position:

6. Establish Metrology and Standards (1989)

The National Institute of Standards and Technology should be a leader in establishing metrology and standards in manufacturing technology for future generations of advanced semiconductors.

" A National Strategy for Semiconductors"
National Advisory Committee on semiconductors
February, 1992

Figure 32

SEMICONDUCTOR TECHNOLOGY

WORKSHOP CONCLUSIONS

SIA SEMICONDUCTOR INDUSTRY ASSOCIATION

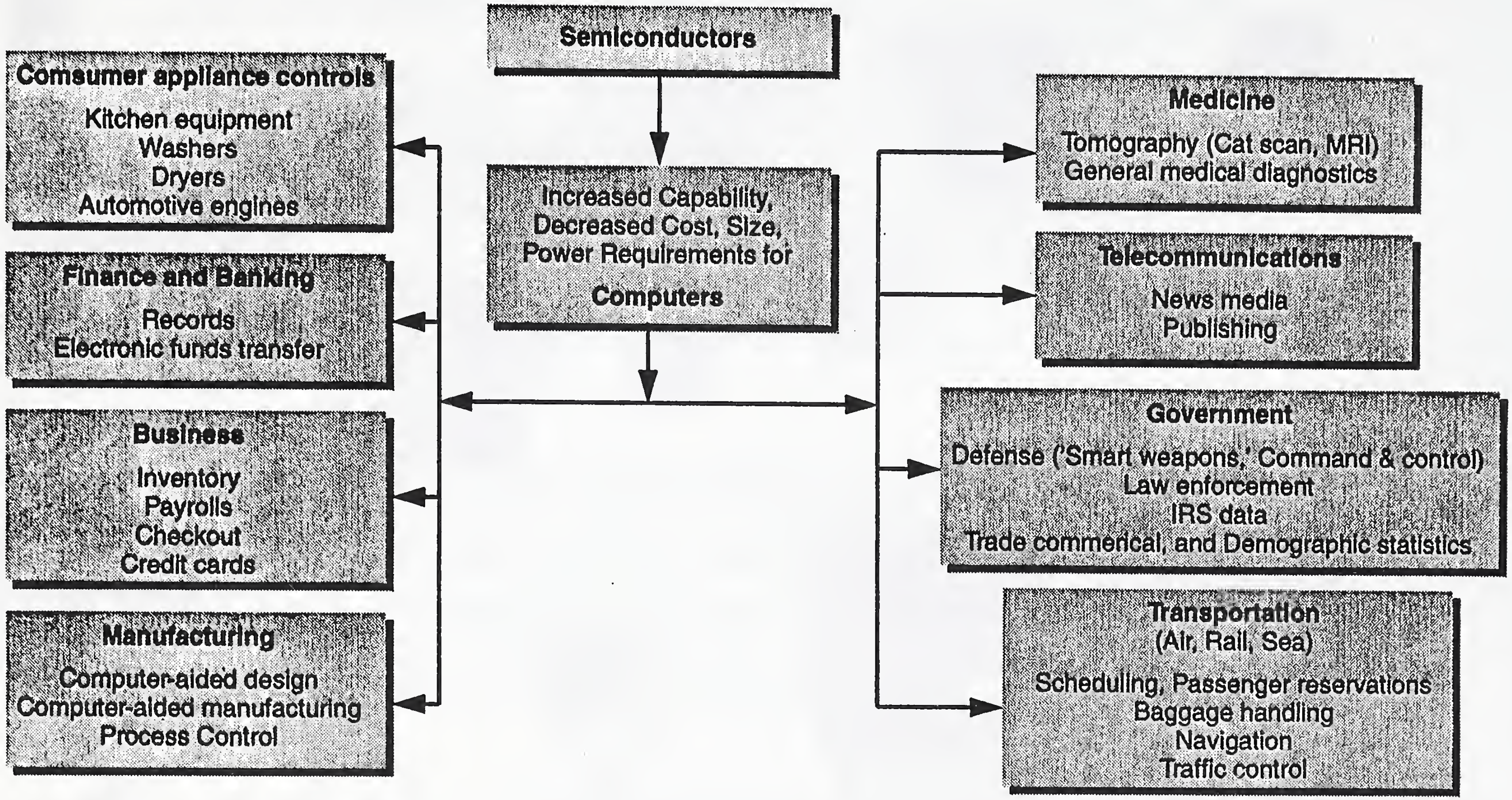
Figure 33

The Program Broadens

- Expanded technical scope required
  - new authority for technology assistance
  - NIST survey of metrology needs
  - industry reports of new requirements
- Additional NIST capabilities enlisted
- A responsive, broadened program is underway and growing

Figure 34

The contribution of semiconductors to the economy



GAO/RCED-90-236 SEMATECH's efforts to strengthen U.S. suppliers

Figure 35

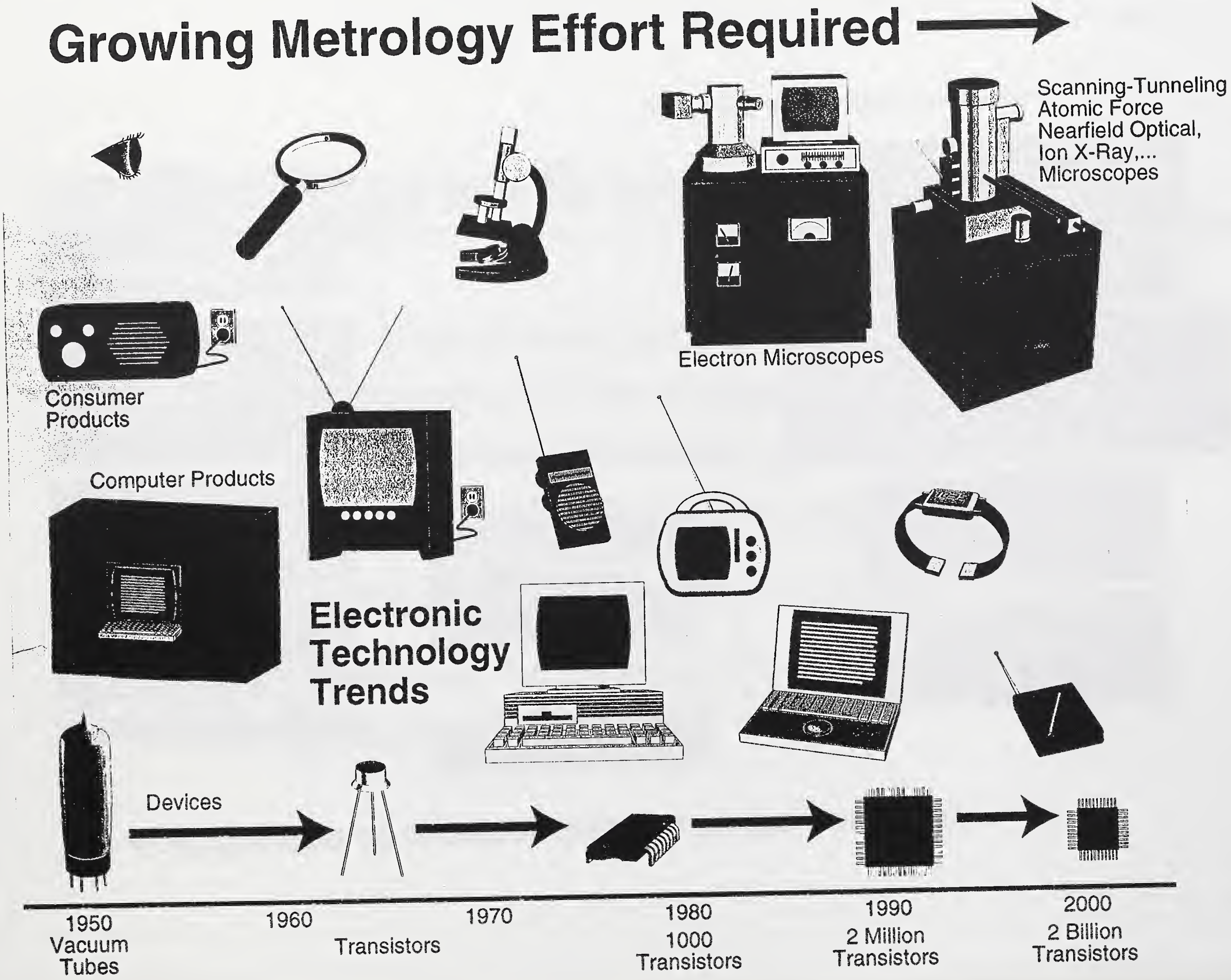

Growing Metrology Effort Required
Scanning-Tunneling
Atomic Force
Nearfield Optical,
Ion X-Ray,...
Microscopes
Electron Microscopes
Consumer
Products
Computer Products
Electronic
Technology
Trends
Devices
1950
Vacuum
Tubes
1960
Transistors
1970
1980
1000
Transistors
1990
2 Million
Transistors
2000
2 Billion
Transistors

Figure 36

“Metrology is a key enabler for equipment design and manufacture, for materials production, for generating data for modeling throughout semiconductor manufacturing, and for final test and evaluation. Without satisfactory metrology, the industry will not be able to follow the Roadmap and will cease to be competitive ....

U.S. manufacturers have the advantage of NIST, the preeminent laboratory in the world in most aspects of the metrological know-how needed for semiconductor manufacturing.”

Semiconductor Industry Association, 1995