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Economic Analysis of NIST's Low-k Materials Characterization Research

Prepared by:
RTI International
for

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Final Report

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Executive Summary

Throughout the 1980s, the semiconductor industry worked to increase the speed and performance of their integrated circuits (IC) and microprocessors by squeezing more and more transistors into a single device. This has been achieved by scaling down the physical dimensions of the transistor elements as well as the distance between them. Today, over one billion transistors are integrated into a single microprocessor.

As the size of transistor components and the distances between them are reduced, an increasingly smaller, densely packed, and highly complex network of conducting wires—referred to as the “interconnect” structure—is also required. Consequently, the material used to insulate interconnect wires has become increasingly important. Although the industry began to focus on finding a replacement for the standard insulating material, silicon dioxide, finding a suitable material that could improve the interconnect delay proved very challenging. In particular, the industry was unable to quantitatively and critically compare different candidate materials. The industry lacked full confidence in the data from existing characterization standard test methods, and as such, analyses lacked precision and were prone to inaccuracy.

In response to industry concerns, SEMATECH[1] initiated a research program aimed at improving the quality of porous materials characterization. NIST worked under a contract for SEMATECH, and between 1998 and 2006, NIST performed characterization analyses of approximately 180 materials. NIST’s contribution also included the development of a variety of novel techniques for materials

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[1] SEMATECH is an industry association funded mainly by U.S. and international semiconductor manufacturing companies to conduct research and coordinate information sharing when appropriate.

characterization and the creation of objective high quality data in much large quantity and at a much lower cost than other research groups would have provided collectively.

ES.1 STUDY SCOPE AND GOALS

The NIST Program Office sponsored this economic evaluation to assess the impact of NIST research conducted between 1998 and 2006. During this time period, a team of NIST researchers led by Wen-li Wu, Eric Lin, Barry Bauer, and Christopher Soles, all from the Polymers Division of the Materials Science & Engineering Laboratory (MSEL), conducted research into low-k materials characterization. The primary focus of this economic impact study is on both the contracted research that NIST conducted for SEMATECH and NIST's internally funded supplemental research.

From 1998 through 2006, NIST supplemented SEMATECH's funding with their internal resources, including from the NIST Office of Microelectronics Programs and MSEL.

Benefits from NIST research activities include

- cost savings that accrued to industry over time in terms of reduced R&D spending on low-k materials characterization,
- reduced low-k materials' adoption costs, and
- reduced production expenses.

In addition to analyzing the net benefits of NIST's investments, RTI's analysis is intended to provide information to the semiconductor industry to support their strategic planning process. Analyzing past impacts and future needs can help the industry and supporting bodies such as SEMATECH focus attention and investment dollars on emerging measurement issues.

ES.1.1 Key Study Objectives

This study quantified the net benefits of industry's use of NIST's materials characterization data and qualitatively analyzed the industry's adoption of X-ray technology for low-k materials analysis. To accomplish these goals, RTI

- described NIST's involvement in low-k materials research (and quantified the costs),

- estimated the industry's use of low-k materials characterization data and adoption of X-ray porosimetry for low-k materials analysis between 1998 and 2006, and
- quantified the benefits of NIST's low-k materials characterization work in terms of R&D cost savings and qualitatively evaluated the impact on quality.

ES.2 LOW-K MATERIALS: TECHNICAL OVERVIEW AND NIST'S INVOLVEMENT

Developing new materials and new material characterization techniques is one of the key ways in which the semiconductor industry has continued to improve their products and processes. The transition that the industry made from using aluminum to copper for interconnect wiring represented one of the most extensive materials transitions that the industry has undertaken (and continues to undertake with less complex semiconductor devices). Developing better materials to insulate these interconnect wires represents another complex challenge that the industry has been working to address since the early 1990s.

During the late 1990s, materials companies developed and tested new low-k materials suitable for semiconductor processing using two main approaches: chemical vapor deposition (CVD) and spin-on dielectric techniques. Suppliers of materials of each type touted the benefits of their materials to customers, but without objective comparison data, manufacturers found themselves in the position of needing to characterize dozens of materials before considering adoption of a single new material.

Analysis of each material was very time-consuming and complex, often requiring manufacturers to outsource analysis work since they did not have the required equipment or skills in-house. The stakes were high: the use of materials based on the CVD process, with which the industry was very familiar, would require significant restructuring of the manufacturing processes of a fab; furthermore, the use of spin-on technology represented a monumental change that could require a company to invest tens of millions of dollars integrating the required new processes into their existing fabs.

ES.2.1 NIST's Involvement

In order to jumpstart the materials characterization process (and hence accelerate adoption of low-k materials) and to prevent extensive duplication of effort by manufacturers and materials and equipment suppliers, in 1998 SEMATECH issued a request for proposals to conduct objective materials characterization of six or seven core properties of low-k materials. Many organizations and universities submitted proposals, and ultimately SEMATECH chose NIST to perform key materials characterization analyses based on several factors: (1) their ability to quantify five of the properties requested by SEMATECH, more than any other proposing organization; (2) their cost-effectiveness; and (3) their willingness to adapt processes based on feedback from SEMATECH.

Between 1998 and 2006, NIST analyzed approximately 180 materials developed to decrease the dielectric constant of the insulating material. NIST received each material blindly (i.e., without any knowledge of the material's creator or properties) and performed unbiased characterization analyses. During the course of its research, NIST also developed several new materials characterization techniques, including X-ray porosimetry, many of which were adopted by industry.

ES.3 QUANTITATIVE ANALYSIS

RTI estimated the net economic benefits accruing to industry from NIST's investment in low-k materials characterization research. RTI focused specifically on the research conducted by NIST under contract for SEMATECH and the additional investments that NIST made to supplement this research. Key contributions analyzed included the following:

- development of objective materials characterization data on approximately 180 low-k materials, and
- development of a variety of new characterization techniques for the analysis of low-k materials.

RTI's quantitative analysis focused on the period from 1998 to 2006. NIST's costs were incurred during the entire period between 1998 and 2006, when NIST scientists conducted materials characterization research on approximately 180 materials. After each candidate material was characterized, NIST prepared a report for SEMATECH that provided data on materials properties and a brief discussion of the results. SEMATECH combined these data with data from other organizations funded to perform materials characterization and periodically distributed summary tables to its members.

The benefits of NIST's work from generating new characterization data began to accrue immediately after the data were first distributed by SEMATECH, beginning in mid-1998, and continued throughout the duration of the study period, which ended in 2006. Although benefits stemming from NIST's research likely continued to accrue after 2006, and some percentage will continue into the future, stakeholders could not quantify benefits beyond R&D cost savings related to the centralized R&D materials' characterization work that NIST performed through 2006.

Additional quantitative analysis related to the benefits of using NIST's new characterization methods and the impact of NIST's research on preproduction and production activities was not possible. Relevant information was not documented by industry in "real-time" when NIST research and results were being utilized, and as such, more complex benefits could not be estimated by industry members.

ES.3.1 Affected Stakeholders

NIST's work affected the entire semiconductor supply chain by significantly improving the ability to analyze the porosity of materials and by providing high quality materials characterization data very quickly to help with screening, both of which resulted in significant cost savings. Impacted stakeholder groups included the following:

- *Materials Suppliers*: Developers and manufacturers of low-k materials using either a spin-on technique, CVD, or another method.
- *Equipment Suppliers*: Makers of CVD, spin-on, and X-ray equipment.
- *Device Manufacturers*: Manufacturers of ICs. Device manufacturers were the most affected group as they could not integrate suitable low-k materials into their processes without extensive characterization testing.

Figure ES-1 conceptualizes the knowledge flows associated with the impact of NIST's research on low-k materials characterization. The figure shows how NIST disseminated information on both materials data and new characterization techniques.

Figure ES-1. Primary and Secondary Knowledge Flows of NIST Low-k Research

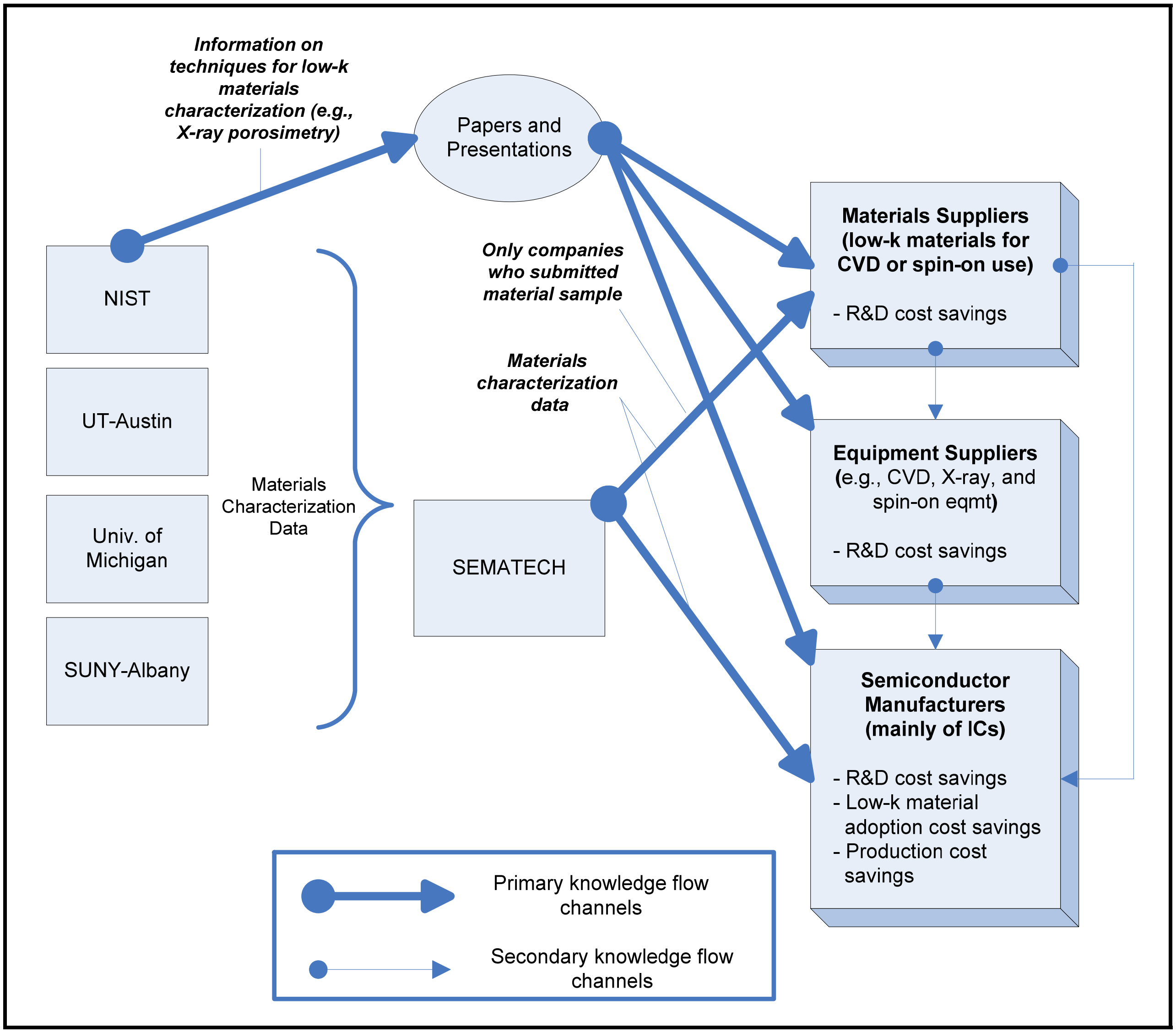

Table ES-1 provides estimates of market coverage of data collected during interviews. The "market" for each stakeholder group was defined from expert and stakeholder estimates of the sales of low-k materials by materials suppliers; sales of X-ray, CVD, and spin-on equipment by equipment suppliers; and research on and planned use of low-k materials by device manufacturers. Secondary information and expert interviews were used to verify market sizes for each stakeholder group.

Table ES-1. Market Coverage of Relevant Stakeholders Participating in Interviews

Stakeholder Group	Number of Firms	Approximated Market Share Represented
Materials Suppliers	5	80%
Equipment Suppliers		
X-ray equipment	2	90%
CVD and spin-on equipment	2	95%
Device Manufacturers	4	80%

ES.3.2 Counterfactual Scenario

RTI sought to determine whether the publicly funded research (1) provided a unique capability—a result otherwise not possible or unlikely to occur (e.g., because private entities would not have been able to see a sufficiently positive private return on investment)—or (2) accelerated development and deployment of low-k materials.

This study focused on how firms would have acted without knowledge flows from NIST. According to interviews with industry stakeholders, NIST provided two key contributions: (1) materials characterization *data* and (2) new low-k materials characterization *techniques* (e.g., X-ray porosimetry). Without these, stakeholders in all three groups indicated that costs would have increased; however, the materials characterization data NIST provided was perceived to be the main contribution. Although some NIST-developed characterization techniques have been used by industry, interviews suggest that competing techniques made NIST's main discovery, X-ray porosimetry, less important.

Broadly, RTI's analysis concluded that NIST's work led to the following categories of industry cost savings:

1. reduced R&D costs,
2. reduced low-k adoption costs, and
3. reduced production costs.

However, industry stakeholders indicated that the main benefit of NIST's work was a reduction in the costs of industry R&D. The use of NIST's research also likely accelerated the development of low-k materials, but industry representatives were not comfortable saying that NIST's work accelerated the deployment or adoption of any low-k materials. As such, quantified benefits in this study were focused on R&D cost savings related to the NIST data.

ES.4 ECONOMIC COSTS AND BENEFITS

SEMATECH paid NIST to conduct low-k materials analysis between 1998 and 2006, and NIST supplemented this funding out of its own budget to conduct additional work developing characterization techniques and advanced processes. NIST's materials characterization data were transferred to SEMATECH at a rate of approximately 15 to 20 material samples per year. Through targeted industry interviews, RTI estimated the level and timing of the use of these data and the effect they had on industry companies in terms of reduced R&D costs—that is, cost savings from avoided or duplicative research. SEMATECH indicated that approximately 10 semiconductor device manufacturers working on low-k materials research received SEMATECH's periodic summaries of characterization results.

With reference to NIST's data, materials suppliers, equipment suppliers, and device manufacturers were able to focus on comparing a handful of low-k materials and testing integration issues as opposed to developing basic materials characterization information, a very labor-intensive, time-consuming process at which few firms were expert. Without NIST, at least a dozen firms would have replicated some portion of NIST's data characterization research for at least 2 to 3 years; however, because of the technical complexity and cost involved, most would not have performed even half the number that NIST did. Using information collected during interviews on the exact timing of cost savings (the alternative spending that would have occurred) RTI developed benefits estimates.

RTI also developed extrapolated benefits estimates that provide a more comprehensive view of the impact of NIST's research in terms of industry-wide R&D cost savings. In order to provide estimates of the total industry benefits, RTI extrapolated from the base case figures. Based on explicit company impact estimates and information on total market sizes by stakeholder group provided during interviews, RTI developed the market share represented by base case estimates. RTI then developed fully extrapolated benefits estimates.

Table ES-2 presents NIST costs, base case benefits, and extrapolated benefits estimates. Fully extrapolated benefits equaled approximately $30 million, or a net present value (NPV) of approximately $24 million.

Evaluation metrics are in Table ES-3. Based on data collected explicitly during interviews (base case), NIST's research resulted in net benefits of approximately $5 million with an NPV of almost $4 million. The benefit-to-cost ratio (BCR) is 2.54. The fully extrapolated case provides more probable metrics by which to gauge the cost-savings impact of NIST's investments. The full extrapolation resulted in calculated net benefits of over $27 million and an NPV of approximately $21 million. The BCR was 9.25.

Table ES-2. NIST Research Costs and Private-Sector R&D Benefits: Base Case and Extrapolated Case ($2008)

Year	Real Cost	Real Cost-Savings Benefits	Real Cost-Savings Benefits: Fully Extrapolated
1998	$37,500	$241,764	$967,056
1999	$396,000	$883,148	$3,100,133
2000	$390,000	$1,049,211	$3,874,158
2001	$490,500	$1,369,407	$5,181,765
2002	$596,000	$1,494,860	$5,612,297
2003	$519,000	$1,250,607	$4,573,384
2004	$406,000	$1,095,317	$3,786,942
2005	$406,000	$883,441	$3,149,187
2006	$101,500	$125,000	$250,000
Total	$3,342,500	$8,392,755	$30,494,923
NPV	$2,555,799	$6,486,258	$23,650,492

Table ES-3. Evaluation Metrics: Base Case and Extrapolated Case

Metric	Value Based on Interview Data	Value Based on Full Extrapolation of Benefits
Costs ($2008)	$3,342,500	$3,342,500
Benefits ($2008)	$8,392,755	$30,494,923
Net Benefits ($2008)	$5,050,255	$27,152,423
Benefit-to-Cost Ratio	2.54	9.25
Net Present Value ($2008)	$3,930,459	$21,094,692

ES-5 SUMMARY REMARKS

RTI's calculated benefits may be considered conservative for several reasons and thus may understate the social benefits associated with NIST's research in low-k. First, R&D cost savings are just one of the benefits that resulted from NIST's knowledge flow chain (see Figure ES-1). NIST's research likely had a significant impact on the cost to adopt low-k materials and possibly enabled faster time to market of ICs with low-k materials, such as Applied Materials' Black Diamond, resulting in lower production costs to meet performance requirements for IC manufacturers.

In addition to the reported R&D cost savings or costs avoided that RTI estimated based on information provided during interviews with company representatives, RTI formulated additional qualitative information relevant to the social benefits associated with NIST's research. Broadly, NIST's work had the following impacts:

1. accelerated the availability of robust low-k materials characterization data (product acceleration benefit),
2. freed up R&D resources for other innovation activities (quality improvement benefit), and
3. provided new low-k materials characterization processes (cost savings and quality improvement benefit).

Although not quantified, NIST's identification and use of X-ray porosimetry resulted in higher quality data than would have otherwise been possible; however, interviews suggest that industry adoption of the X-ray technique was limited. Although X-ray porosimetry provides higher quality data than alternate techniques, X-ray reflectivity in its current form is a costly procedure as compared to such alternate techniques. Without NIST's involvement, interviews suggested that the use of X-ray for low-k materials analysis today would be even lower, and the value of NIST's data would have been reduced. Further, X-ray porosimetry is also the most likely technique to be considered in future production environments.

Two changes in NIST's activities were suggested by several participants. First, several manufacturers commented that they had hoped that NIST would continue to conduct materials characterization research in a "turn the crank" fashion beyond 2007. Second, both manufacturers and equipment suppliers mentioned that NIST could have done more to help with the transfer of its X-ray porosimetry technique out of the lab and into the market as a product.

1 Introduction

This report documents and quantifies the net economic benefits accruing from the National Institute of Standards and Technology's (NIST's) investments in low-k materials characterization research during the late 1990s and early 2000s.

Throughout the 1980s, the semiconductor industry worked to increase the speed and performance of their integrated circuits (IC) microprocessors by squeezing more and more transistors into a single device. This has been achieved by scaling down the physical dimensions of the transistor elements as well as the distance between them. Today there are well over one billion transistors integrated into a single microprocessor.

As the size of transistor components and the distances between them are reduced, an increasingly smaller, densely packed, and highly complex network of conducting wires—referred to as the "interconnect" structure—is also required. With over one billion transistors now squeezed into the area of a few square centimeters, the length of the copper wiring used to integrate these transistors into a functional device is measured in miles.

As a result of the incredible scaling of device components, the speed and the performance of microprocessors are no longer dictated by the speed of individual transistor elements. Rather, the device performance is increasingly dictated by how fast current can be moved into and out of the transistor elements through the interconnect structure. Thus, the speed of today's semiconductor devices is largely based on two important material properties: the electrical resistance (R) of the metal used in the conduction lines and the capacitance (C)—a measure of how much electrical charge can be stored in a material under a given voltage or potential—of the material used to isolate and insulate the individual conduction lines.

In the early 1990s, the interconnect delay was identified as a major barrier to improving the speed of devices. As a result, the semiconductor industry embarked on a major effort to improve the interconnect delay by reducing the capacitance and the resistance of the materials used in the interconnect structure. Lowering the capacitance could be approached in two main ways: either altering the physical dimensions, or geometry, of a device, or reducing the dielectric constant (k) of the insulating material itself. In terms of materials development, the industry focused their attention on developing two types of new materials: (1) better conductors to be used as wires in the interconnect structure and (2) insulator materials to isolate the conduction lines. As a result of its lower resistance, copper was identified as a replacement for the industry standard aluminum, which had been used for interconnect wires. In the mid-1990s IBM identified the process by which copper could be integrated into the semiconductor fabrication processes.

Throughout the 1990s, the standard insulating material used by the semiconductor industry was silicon dioxide. The deposition and fabrication technology for silicon dioxide was very mature and reliable. However, finding a suitable material with a lower dielectric constant than silicon dioxide proved to be more challenging than identifying copper as a replacement for aluminum for interconnect wires. In addition to achieving a low dielectric constant, the successful candidate material needed to satisfy a stringent list of properties, including (1) a high modulus to withstand the abrasive polishing process, (2) a low coefficient of thermal expansion to minimize potentially fatal thermal mismatch stress with the silicon and other materials in the integrated circuit, and (3) the thermal resistance to withstand temperatures in excess of 400°C.

Through a series of international conferences and industrial consortiums, the community identified that the search for suitable low-k material to replace silicon dioxide was a high priority for the semiconductor industry. Dozens of companies and academic research institutions, mainly in the United States, initiated research programs aimed at developing low dielectric constant (low-k) materials. Although it was not exactly clear which type of material would ultimately succeed in replacing silicon dioxide, it was generally agreed that such low-k materials needed to be either naturally porous or artificially made porous.[2]

By the late 1990s, the race to identify suitable porous materials to replace silicon dioxide was well underway. Materials suppliers to the semiconductor industry and academic research groups began developing a wide range of porous materials for consideration. However, this process quickly revealed a weakness within the community—the inability to quantitatively and critically compare different candidate materials. The industry lacked full confidence in the data from existing characterization standard test methods, and as such, analyses lacked precision and were prone to inaccuracy. The economic impact of this situation was R&D inefficiency; materials characterization work was slow and duplicative, and without standards in place, research results could not easily be shared.

In response to industry concerns, SEMATECH[3] decided to initiate a research program aimed at improving the quality of porous materials characterization. After realizing that it lacked the technical capabilities to analyze the characteristics of pores, SEMATECH released a request for proposals (RFP) to conduct analysis of seven materials properties that seemed to be the most promising at the time. NIST was awarded one of several contracts and subsequently provided technical capabilities to SEMATECH—NIST developed new characterization techniques and provided data on low-k materials.

1.1 NEED FOR NIST'S INVOLVEMENT

In interviews with RTI, SEMATECH representatives indicated three key reasons why NIST was uniquely qualified to support this initiative:

- *NIST's rare technical capabilities*: NIST was one of the only applying organizations that had developed a capability to analyze thin films on the wafer (as opposed to analyzing the bulk material). The SEMATECH RFP stipulated that the measurements be taken on-wafer since properties of a material in thin film form may be different from those in bulk form. Taking measurements this way would ensure suitability for both R&D and production environments.

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[2] The most effective insulating media is a vacuum that has a k = 1, whereas fully dense silicon dioxide has a dielectric constant of k ~ 4.2. It is extremely difficult to find a fully dense material with a dielectric constant less than 4.2 that satisfies all the other materials property requirements for an interconnect material. However, adding pores to a silicon dioxide-like material was found to be an effective way to further reduce k.

[3] SEMATECH is an industry association funded mainly by U.S. and international semiconductor manufacturing companies to conduct research and coordinate information sharing when appropriate.

- *NIST's broad research capabilities*: NIST offered to conduct multiple analyses (i.e., provide results on several different key materials properties), whereas other organizations proposed to analyze only one or two materials properties for more money than NIST proposed to analyze several. NIST proposed to develop an integrated measurement platform based on X-ray techniques and neutron scattering to analyze pores, ion beam techniques to determine chemical composition, and thermal property analyses such as stability and thermal expansion coefficient analysis.
- *NIST's adaptability*: Finally, NIST researchers were capable of modifying analysis techniques and procedures to evaluate the materials properties in the format requested by SEMATECH.

In addition to NIST's involvement, SEMATECH also worked with several other organizations, including the University of Texas at Austin, the University of Michigan at Ann Arbor, the Massachusetts Institute of Technology (MIT), the University of Minnesota, and the State University of New York (SUNY) at Albany. The University of Texas group conducted analysis of the dielectric constant, thermal stability, adhesion, mechanical properties, thermal conductivity, and chemical signature. The University of Michigan focused on porosity analysis, using positron annihilation lifetime spectroscopy (PALS) to provide porosity information to compare with NIST's X-ray results. SEMATECH also performed some internal materials characterization itself, including trace metal analysis and analysis of film thickness, adhesion, and roughness (Wetzel et al, 2001).

Between 1998 and 2006, NIST performed characterization analyses of approximately 180 materials. The data generated by NIST were provided to SEMATECH, which disseminated summary data to their member companies and the suppliers who submitted candidate materials for evaluation. NIST provided a broad scope of materials characterization research. Without NIST's extensive capabilities and relative research cost-effectiveness, SEMATECH would have been unable to coordinate the breath of materials research. Further, a number of individual organizations would have conducted separate analyses of the same materials.

The objective nature of the research conducted by NIST, SEMATECH, and SEMATECH's other research partners is particularly important. Without their involvement, much of the materials characterization data would likely have been developed by materials suppliers who (a) had an interest in developing data that showed the suitability of their particular material for the semiconductor manufacturing process and (b) did not share standard test methods that would allow for a rational comparison of the materials performance from different companies. The objective, standard comparison of candidate materials among different suppliers was critical for identifying the best replacement for silicon dioxide.

During this process, NIST also developed a variety of novel techniques for materials characterization, many which were subsequently adopted by the industry. Without NIST, SEMATECH would have had difficulty finding another organization to develop the techniques and produce the quantity of high quality data that NIST provided at even close to the same cost, and the industry as a whole would have suffered.

1.2 STUDY SCOPE AND GOALS

The NIST Program Office sponsored this economic evaluation as a retrospective investment analysis. NIST is interested in the impact that advances in measurement infratechnologies, generic technologies, and associated standards have had on the semiconductor industry. This study focused on NIST's research on low-k materials characterization, the impact of which was quantified in terms of R&D cost savings.

This analysis specifically focuses on the impact of NIST research conducted between 1998 and 2006. During this time period, a team of NIST researchers led by Wen-li Wu, Eric Lin, Barry Bauer, and Christopher Soles, all from the Polymers Division of the Materials Science & Engineering Laboratory (MSEL), conducted research into low-k materials characterization. The primary focus of this economic impact study is on both the contracted research that NIST conducted for SEMATECH and NIST's supplemental research investment.

NIST contributed a substantial fraction of their own internal resources to develop the measurement technologies. The Polymers Division's initial efforts were funded through the NIST Office of Microelectronics Programs, an internal organization whose mission is to facilitate metrology development for the semiconductor industry. From 1998 through 2006, NIST supplemented SEMATECH's funding with their internal resources, including from the NIST Office of Microelectronics Programs and MSEL.

Benefits from NIST research activities include

- cost savings that accrued to the industry over time in terms of reduced R&D spending on low-k materials characterization,

- reduced low-k materials' adoption costs, and
- reduced production expenses.

The direct costs of NIST's research activities primarily include NIST labor (i.e., conducting research, writing papers and presenting at conferences) to develop new characterization techniques and data—with some associated equipment and materials costs.

In addition to analyzing the net benefits of NIST's investments, RTI's analysis is intended to provide information to the semiconductor industry to support their strategic planning process. Analyzing past impacts and future needs can help the industry and supporting bodies such as SEMATECH focus attention and investment dollars on emerging measurement issues.

1.2.1 Study Limitations

This analysis focuses mainly on the R&D cost savings resulting from NIST's research. However, there is significant uncertainty behind the quantitative results for several reasons.

First, because NIST's research results were aggregated with that of other researchers working for SEMATECH, industry stakeholders interviewed for RTI's study found it very difficult to discern the impact of NIST's research separately from the impact of other SEMATECH-funded characterization activities.

Second, the benefit estimates presented in this report are likely underestimates because additional benefits identified by interview participants were unable to be accurately quantified. This report provides a qualitative analysis of these benefits, the existence of which implies that the total benefit of NIST's work is likely much greater than the estimates reported in this study would suggest.

One set of benefits that could not be quantified involved NIST's development of several new characterization techniques. For example, X-ray porosimetry (XRP), a technique first identified and described by NIST researchers, is viewed by the industry as an important tool for porosity analysis. Results from porosity analysis using this technique are in many ways superior to competing technologies, such as ellipsometric porosimetry (EP); however, adoption of X-ray equipment for pore analysis has been very slow largely because EP became a more cost-effective option. According to industry representatives, NIST helped with the development of both XRP and EP; however, the industry was not able to trace the impact of NIST's work on the development of EP.

NIST's work also had, and will continue to have, an impact on the availability and high quality of semiconductor devices and likely helped reduce the costs and speed up the timing of low-k materials adoption. The magnitude of these benefits is likely to be quite large, but largely unquantifiable.

1.2.2 Key Study Objectives

This study quantified the net benefits of the semiconductor industry's use of NIST's materials characterization data and qualitatively analyzed the industry's adoption of X-ray technology for low-k materials analysis. To accomplish these goals, RTI

- described NIST's involvement in low-k materials research (and quantified the costs),
- estimated the industry's use of low-k materials characterization data and adoption of X-ray porosimetry for low-k materials analysis between 1998 and 2006, and
- quantified the benefits of NIST's low-k materials characterization work in terms of R&D cost savings and qualitatively evaluated the impact on quality.

1.3 REPORT ORGANIZATION

The remainder of this report is organized as follows:

- Chapter 2 offers a technical review of the role of low-k materials in the semiconductor manufacturing process and NIST's related research program.
- Chapter 3 describes the methodology that RTI employed to assess the net economic benefits associated with NIST's investments in low-k materials characterization.
- Chapter 4 discusses the findings from the evaluation analysis and provides a discussion of qualitative benefits.
- Chapter 5 concludes this report with a summary of findings.

2 Low-k Materials: Technical Overview and NIST's Involvement

Developing new materials and new material characterization techniques is one of the key ways in which the semiconductor industry has continued to improve their products and processes. The transition that the industry made from using aluminum to copper for the interconnect wiring represented one of the most extensive materials transitions that the industry has undertaken (and continues to undertake with less complex semiconductor devices). Developing better materials to insulate these interconnect wires represents another complex challenge that the industry has been working to address since the early 1990s.

ICs, the building blocks of semiconductor components, are composed of individual semiconductor devices (e.g., transistors), which are connected by metal wires, often referred to as wire lines, lines, or interconnects. These interconnects are separated by insulating material, called dielectrics, to prevent signals (and electric charge) from separate wires from bleeding over to neighboring lines (i.e., "cross talk"). The impact on performance of the dielectric insulator includes not only the ability to provide electric insulation and reduce cross-talk, but it also influences the speed at which information is transferred through the interconnected semiconductor device. This directly impacts the clock speed of the microprocessor.

A widely used metric of performance in an interconnect system is its interconnect delay, which represents a measure of the time-delay for signal propagation. The delay is directly related to the product $R \times C$, where R denotes the resistance of the interconnect line and C denotes the effective capacitance between adjacent lines.

R and *C* are dependent on a number of factors, which can be grouped into two main categories: geometrical (physical) properties and material properties. Geometrical properties include: thickness of the lines, width of the lines, closeness of the lines (i.e., horizontal and vertical distances between adjacent lines), and length of the lines. Material properties include the resistivity of the metal used for wires and the dielectric constant (k) of the interconnect insulating material (i.e., the dielectric).

Each of the geometrical and material properties listed above can impact either *C* or *R*, and hence affect the delay. For example, longer wires cause a proportional increase in resistance as well as an increase in capacitance, and hence increase the delay significantly. Materials with lower dielectric constants are essential to improving IC performance and meeting industry goals. This chapter provides a brief historical summary of the past low-k materials research efforts, and a description of NIST's and SEMATECH's involvement in low-k materials characterization.

2.1 LOW-K MATERIALS HISTORY

Throughout the 1980s, the semiconductor industry primarily focused on improvements related to the speed of an individual transistor and enhanced performance through scaling—improving the performance of an IC by squeezing more transistors (logic elements) into a single device. But by the early 1990s, the distances between device components were becoming incredibly small, and the relative effect of the interconnect delay became a greater portion of the overall signal propagation delay and at some point could no longer be neglected. Companies realized the need to improve the interconnect delay by making changes to the materials used for wires and the materials used to insulate the wires.

As feature sizes of the elements in IC chips continued to decrease, both line widths and the spacing between the conduction lines also shrank. This scaling, or the integration of more and more transistor elements, also meant that the total length of the interconnect wires was increasing exponentially and that each microprocessor soon contained several miles of conduction lines. The total resistance (R) of the interconnect structure became a significant factor affecting chip performance.

At the same time, the capacitance (C) between the wires was increasing proportionally to the decreasing spacing between the wires. The result was that as the feature sizes decreased, RC delay increased conspicuously. Even as the speed of transistors increased dramatically, the interconnect delay became a limiting factor.

The 1994 National Technology Roadmap for Semiconductors (NTRS)—the U.S. industry's forward-looking technology strategy document—stated that materials with a lower dielectric constant ("low-k materials") would be needed for interconnect insulating material as the feature sizes of semiconductor devices, or chips, became smaller. The NTRS projected that within 10 years the industry should be able to achieve a standard dielectric constant of less than 1.5 in their production interconnect material (Semiconductor Industry Association, 1994). A dielectric constant of around 4.2 for silicon dioxide (SiO_2) was the standard material in use in 1994 (Brown, 2003).

SEMATECH, an industry consortium, began to work on a research agenda with suppliers and manufacturers that included the identification of the most important materials' characteristics needed for low-k materials. In late 1994, at a public NTRS conference in Colorado Springs, Colorado, a major materials supplier announced that it had developed a spin-on material[4] with a k value of 2.7 (Case, 2004). The development of low-k materials seemed to be only a few years away.

By 1997, chip manufacturers were using insulating materials with dielectric constants below 4.0. Fluorosilicate glass (FSG), which was created by adding fluorine to silicon dioxide, had a k value of around 3.6 and required very little change in the production process for semiconductor manufacturers. Thus, FSG was quickly and widely adopted by the industry. However, very little progress had been made towards identifying suitable materials with a dielectric constant below 3.0, which would likely require less dense (i.e., more porous) materials.[5]

Companies had difficulty identifying suitable materials because materials' properties changed significantly when the k value was lowered below a certain level. Lower k materials were generally softer, mechanically weaker, and did not adhere well to silicon or metal wires. Further, low-k materials in existence did not withstand conventional processing (i.e., they would crack or delaminate). However, the importance of low-k

[4] See description of spin-on-based low-k materials in text box on page 2-5 and in Figure 2-2.

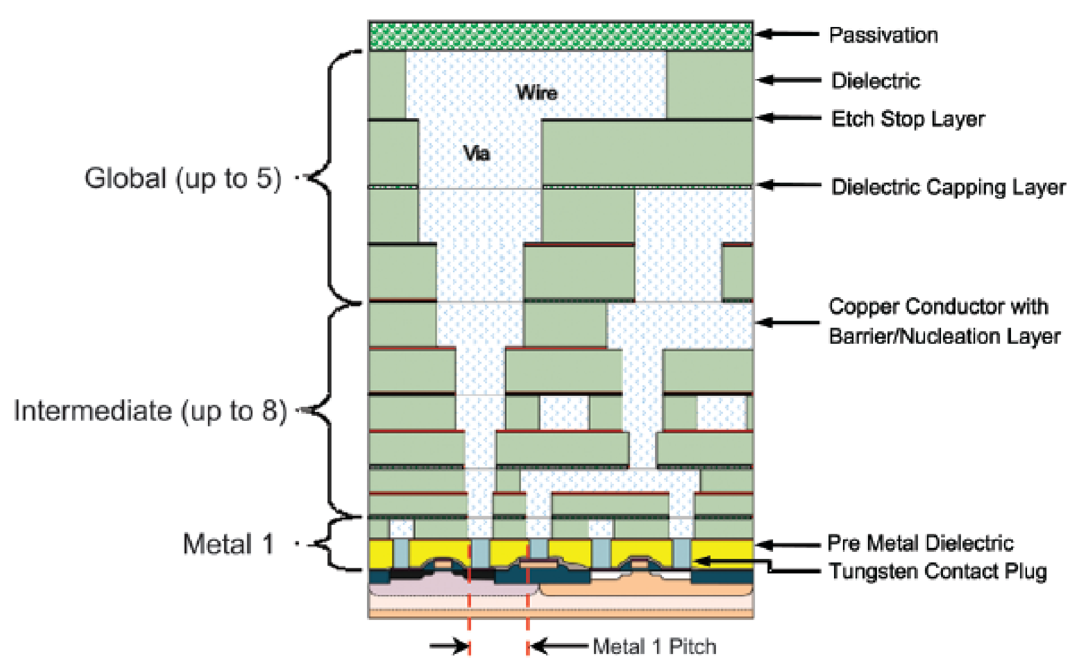
[5] All materials are porous, but the degree of porosity can differ greatly. Some materials' molecules arrange themselves in a tighter lattice structure, resulting in less porosity, while others have a looser lattice structure, resulting in more porosity. Materials' porosity is often thought of as one of three types: (1) "micro-porous" materials have pores that are less than 2 nanometers (20 Å) in width; (2) "meso-porous" materials have pores that are between 2 and 50 nanometers (20-500 Å) in width; and (3) "macro-porous" materials have pores that are greater than 50 nanometers (500 Å) in width.

materials to the industry was highlighted by the 1997 edition of the NTRS, which suggested that low-k materials were essential for the future progress of the industry and stated that low-k "materials that simultaneously meet electrical, mechanical, and thermal [integration] requirements have been elusive" (Semiconductor Industry Association, 1997, p. 99). New materials and new materials characterization processes were needed.

In the years that followed, low-k materials research continued, but improvement in chip performance was primarily made possible because of technical accomplishments made in other areas. In particular, the transition to copper wires resulted in a significant reduction in interconnect delay and forestalled the need for low-k materials.

In 1998, IBM announced a new hierarchical wiring architecture (Andricacos, 1998; Andricacos et al., 1998), based on the so-called "damascene" process which made possible fabrication of multilevel copper wires with a thickness of several microns and a width of less than a micron. Figure 2-1 shows this new architecture. The transition to copper, which has lower resistivity than aluminum, resulted in a reduction in R.

Figure 2-1. IC Architecture Introduced by IBM



Source: Case (2004).

Alternate Low-k Materials Processing Approaches

Chemical Vapor Deposition (CVD): CVD processes are widely used in the semiconductor industry to dope silicon dioxide (SiO_2) into its semiconducting form used in the transistor using dopants such as boron or phosphorous. Therefore, there are good reasons to adapt these CVD processes to produce porous, insulating forms of SiO_2. Rather than phosphorous and boron, gases are added to the CVD precursors containing silicon (Si), oxygen (O), hydrogen (H), and carbon (C) to form derivatives of SiO_2, with some of the Si-O bonds replaced by Si-CH_3 bonds. The resulting compound has a more open lattice structure (i.e., greater porosity). The built-in microporosity leads in turn to a reduced dielectric constant. This approach has the benefit of allowing manufacturers to use the same CVD equipment already operating in fabs, modified only by additional gas delivery lines. Thus, adoption of such a process requires a relatively low integration cost and gives the industry a level of confidence in the new process. However, the lowest k of a known CVD film is 2.2.

Spin-On: Low-k and even ultra-low-k (k<2.2) dielectrics have also been produced by another technique referred to as "spin-on." The most common spin-on approach has used a chemical mixture based on a porous SiO_2 structure, although silsesquioxanes (e.g., hydrogen silsesquioxane [HSQ] and methyl silsesquioxane [MSQ]) and organic materials have also been employed. As shown in Figure 2-2, the resulting chemical compound is dripped onto a spinning surface and then converted at elevated temperatures. Companies developing spin-on dielectrics suggested that the porosity could be more easily added to and controlled by these types of films, and thus lower k values would be possible as compared to CVD-based materials. However, the additional cost to the industry of making such a significant change to their process would be very large (i.e., potentially in the tens of millions of dollars per fab) since the transition would require new equipment and significant process flow changes.

See Figure 2-2 for a pictorial comparison of the steps involved in CVD and spin-on processes.

During the late 1990s, materials companies continued to develop and test new low-k materials suitable for semiconductor processing using two main approaches: chemical vapor deposition (CVD) and spin-on dielectric techniques. These two techniques have very different technical characteristics and economic consequences as described in the text box above and shown in Figure 2-2.

By 1999, low-k materials were being developed by at least 10 companies—including Applied Materials, Shipley, Rohm & Haas, Dow Chemical, Dow Corning, Honeywell, and JSR Microelectronics. Each materials supplier touted the benefits of their materials to customers, but without objective comparison data, manufacturers found themselves in the position of needing to characterize dozens of materials before considering adoption of a single new material. Analysis of each material was very time-consuming and complex, often requiring manufacturers to outsource analysis work since they did not have the required equipment or skills in-house. The stakes were high: the use of materials based on the CVD process, with which the industry was very familiar, would

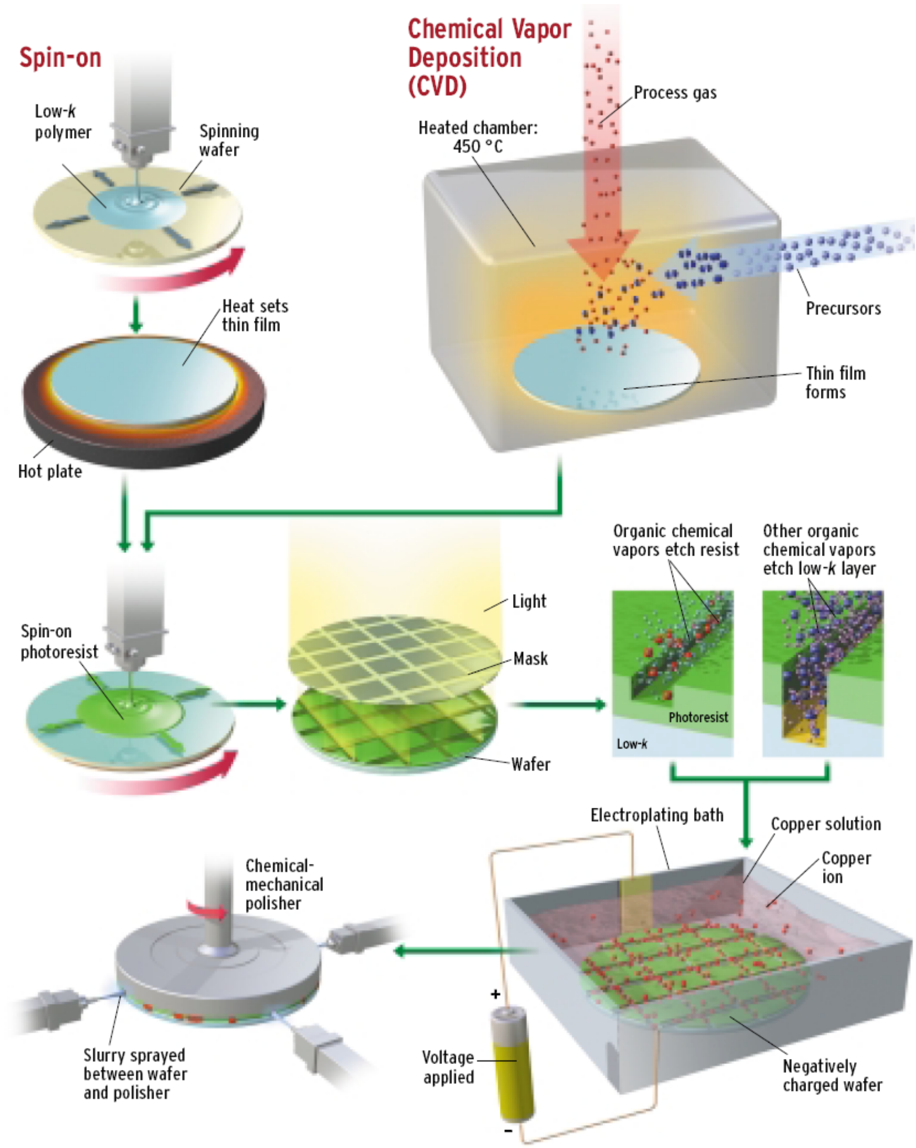
Figure 2-2. Spin-on versus Chemical Vapor Deposition (CVD) Techniques

Lowdown On Low-*k* Processes

The spin-on and chemical vapor deposition processes [starting from top] differ basically in how they deposit a thin low-*k* dielectric film on a silicon wafer.

Spin-on drips its polymeric material onto a spinning wafer under normal atmospheric pressure. CVD starts with a gas and precursor molecules and heats them in a vacuum chamber. The heat "cracks" the materials and the film is deposited.

Thereafter both processes proceed similarly [middle]. A photoresist is added, the interconnection pattern is exposed on the wafer, and the resist and low-*k* film are etched away. Signal-conducting copper is plated onto the film pattern [bottom] and the entire wafer is treated to a chemical-mechanical polishing.



Source: Brown (2003).

require significant restructuring of the manufacturing processes of a fab; furthermore, the use of spin-on technology represented a monumental change that could require a company to invest tens of millions of dollars integrating the required new processes into their existing fabs. As such, semiconductor manufacturers demanded the most accurate information possible on the low-k materials they were considering adopting.

2.2 SEMATECH AND NIST INVOLVEMENT

In order to jumpstart the materials characterization process (and hence accelerate adoption of low-k materials) and to prevent extensive duplication of effort by manufacturers and materials and equipment suppliers, in 1998 SEMATECH issued a request for proposals to conduct objective materials characterization of six or seven core properties of low-k materials. Many organizations and universities submitted proposals, and ultimately SEMATECH chose NIST to perform key materials characterization analyses based on several factors: (1) their ability to quantify five of the properties requested by SEMATECH, more than any other proposing organization; (2) their cost-effectiveness; and (3) their willingness to adapt processes based on feedback from SEMATECH.[6] Once the project began, each organization had to figure out how to characterize thin porous film on a substrate, and NIST developed their techniques very quickly. According to a former SEMATECH Interconnect Program Manager, NIST provided information faster than the other organizations involved in this research and at a lower cost.[7]

Between 1998 and 2006, NIST analyzed approximately 180 materials developed to decrease the dielectric constant of the insulating material. NIST received each material blindly (i.e., without any knowledge of the material's creator or properties) and performed unbiased characterization analyses.

[6] SEMATECH also outsourced the characterization of certain materials properties to other universities and research institutions; however, according to SEMATECH representatives, NIST provided the most complex characterization activities. The characterization work broke down as follows: (1) NIST used X-ray reflectivity and neutron scattering to characterize the following properties: thickness, total film density, density of the matrix without pores, porosity, average pore size, moisture uptake, and thermal expansion coefficient. NIST also analyzed the chemical composition of the film, which was needed to determine the above properties. (2) The University of Michigan used positron annihilation spectroscopy to determine average pore size and pore interconnection length. (3) The University of Texas at Austin characterized film adhesion, mechanical properties, and chemical composition by Fourier transform infrared (FTIR) spectroscopy, moisture uptake, and thermal expansion coefficient. (4) SUNY-Albany used Rutherford Backscattering Spectrometry (RBS) and nuclear reaction analysis to characterize chemical composition and porosity. See overview of roles in Wetzel et al. (2001).

[7] There was some overlap in work performed by NIST, Michigan, Texas, and SUNY because SEMATECH originally was interested in examining multiple techniques to measure the properties of films. SEMATECH later dropped SUNY but continued with NIST, Michigan, and Texas. Even though NIST was part of a larger characterization program, NIST was the largest contributor. The J105 project, as it was known within SEMATECH, also included a large effort within SEMATECH labs to deposit porous films and integrate them into an IC fabrication flow. SEMATECH needed the materials characterization results to understand what film properties affected manufacturers' ability to process and integrate these films. From this combined understanding, SEMATECH could feed information back to film suppliers concerning what properties needed to change and how.

NIST characterized approximately an equal number of CVD and spin-on materials during the 9 years in which they conducted materials characterization for SEMATECH. In the first year, between mid-1998 and mid-1999, NIST and SEMATECH worked together to coordinate the exact analysis procedures that would be used and how results would be reported.

Thereafter, NIST's work proceeded at a rate of approximately four to five materials per quarter. After each material was characterized, NIST sent SEMATECH a report summarizing their results. SEMATECH would then compile the most important data and provide comparison tables to member companies and the companies that supplied the materials. SEMATECH did not assess the "worthiness" or lack thereof of specific materials.

NIST became a trusted partner for the industry as companies sought to identify low-k materials that would meet manufacturing requirement and product quality needs. Materials suppliers came to rely on NIST and SEMATECH to help them develop their products. Upon the release of each set of NIST's characterization results to SEMATECH's member companies, SEMATECH would also provide feedback to the materials suppliers, suggesting how they could improve their materials' properties based on NIST's results. As a result of such feedback, JSR, among others, decided to discontinue some of its materials development work and begin developing other new material types.

As a result of NIST's work, research efforts on many materials that were determined not to be ready for widespread industry adoption were halted. Dow Chemical's SiLK, a spin-on dielectric, is an example of one such material that was in the process of being adopted by many manufacturers in the industry, including IBM and United Microelectronics Corp. (UMC), before it was determined that the integration challenges were prohibitive for manufacturing at the 90nm node (Goldstein, 2003). Although NIST and SEMATECH were not directly responsible for the decision by manufacturers not to adopt SiLK, NIST and SEMATECH's work was important in broadly identifying the scale and nature of production problems that would accompany many spin-on dielectrics, such as SiLK.[8] In this way, NIST's work might have helped the industry save hundreds of millions of dollars in new materials adoption costs.

[8]Low-k materials using spin-on technology is a relatively small market in comparison to the market for CVD-based low-k materials. Applied Materials' Black Diamond material,

2.3 NEW NIST MATERIALS CHARACTERIZATION TECHNIQUES

NIST's low-k materials characterization research utilized a variety of techniques, many of which had never been used on low-k materials previously.

In particular, NIST used small angle neutron scattering (SANS), small angle X-ray scattering (SAXS), and X-ray reflectivity to characterize the porosity. In addition, NIST developed a unique ion beam scattering procedure, based on Rutherford Back Scattering (RBS), grazing angle backscattering (GBS), and forward recoil elastic scattering (FRES) to determine the atomic composition of the unknown materials provided by SEMATECH (Wetzel et al., 2001). Knowing the atomic composition of these unknown films was critical to extracting quantitative data regarding their density and porosity.

Of the greatest significance, NIST first identified X-ray reflectivity as a way to accurately measure low-k materials' pore size, absolute material density, and depth profile. X-ray *porosimetry*, the name NIST researchers gave to their technique, offered significant improvement over ellipsometer based porosimetry (EP) and PALS, which were being used for pore analysis but required assuming various models to extract physical parameters[9] and resulted in some change in materials properties. SANS was also used to provide critical data; however, because it required access to a nuclear reactor, this technique was not a practical solution for many organizations.[10]

Many of NIST's techniques quickly became adopted as industry standards. During the early 2000s, the industry significantly improved their characterization techniques using NIST's data and measurement techniques, and in 2004 NIST published a recommended practice guide on X-ray porosimetry (Soles et al., 2004). Today, with the help of NIST's work establishing standard practices, the industry is generally able to conduct the majority of materials characterization work in-house.

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based on a CVD process, became the industry standard around 2003 or 2004 and continues to dominate the market.

[9] Using EP, in some cases the thickness and the index of refraction are correlated and cannot be extracted separately. Moreover, the interface and surface roughness may influence the measurement results. X-ray reflectivity allows for the independent determination of the film thickness, interface and surface roughness, index of refraction, and density. However, X-ray techniques were expensive to adopt and the analysis took longer than with EP.

[10] IBM, among several non-governmental organizations, did have a nuclear reactor with which they used neutron methods for low-k characterization.

In summary, NIST's work provided centralized, rapid, materials characterization data as well as new materials analysis techniques that became industry standards (see Appendix A for a list of significant papers published by NIST researchers on new techniques and the results of materials characterization efforts). More specifically, NIST's research resulted in the following:

- cost savings to IC manufacturers, materials suppliers, and equipment suppliers resulting from NIST's centralized data analysis;
- faster time to market of ICs with low-k materials, such as Applied Materials' Black Diamond, that provide performance benefits to products and profits to materials suppliers and IC manufacturers;
- cost savings to materials suppliers and IC manufacturers resulting from the use of X-ray reflectivity and other NIST-developed techniques; and
- cost savings from avoided implementation of faulty or costly materials processes into new fabs.

3 Quantitative Analysis

RTI estimated the net economic benefits accruing to the industry from NIST's investment in low-k materials characterization research. RTI focused specifically on the research conducted by NIST under contract for SEMATECH and the additional investments that NIST made to supplement this research. Key contributions analyzed include the following:

- development of objective materials characterization data on approximately 180 low-k materials, and
- development of a variety of new characterization techniques for the analysis of low-k materials.

These two contributions combined to help the semiconductor industry analyze and ultimately select low-k materials much more quickly and efficiently than would have been possible otherwise.

This study focused on quantifying NIST's costs and the R&D cost savings benefits related to the generation of new materials characterization data. Additional benefits, such as the impact of NIST's work on materials adoption costs and production costs, as well as any product quality improvements, are discussed qualitatively. Describing NIST's costs and the resulting qualitative and quantitative benefits is the focus of this chapter.

3.1 ESTABLISHING THE PERIOD OF ANALYSIS

RTI's quantitative analysis focused on the period from 1998 to 2006. NIST's costs were incurred between 1998 and 2006 when NIST scientists conducted materials characterization research on approximately 180 materials. After each candidate material was characterized, NIST prepared a report for SEMATECH that provided data on materials properties and a brief discussion of the results.

Table 3-1. NIST's Annual Low-k Materials Analyses Reported to SEMATECH

Year	Number of Sample Materials' Results Reported
1999	20
2000	27
2001	29
2002	16
2003	16
2004	50
2005	21
Total	179

SEMATECH combined these data with data from other organizations funded to perform materials characterization, and periodically distributed summary tables to its members. Table 3-1 shows the number of samples NIST characterized and reported to SEMATECH each year. The benefits of NIST's work generating new characterization data began to accrue within the industry immediately after the data were first distributed by SEMATECH, beginning in mid-1998, and continued throughout the duration of the study period, which ended in 2006. Although benefits stemming from NIST's research likely continued to accrue after 2006, and some percentage will continue into the future, stakeholders could not quantify R&D cost savings benefits beyond 2006.

3.2 AFFECTED STAKEHOLDERS

NIST's work affected the entire industry by significantly improving the ability to analyze the porosity of materials and by providing high quality materials characterization data very quickly to help with screening, both of which resulted in significant cost savings. Impacted stakeholder groups included the following:

- *Materials Suppliers*: Developers and manufacturers of low-k materials using either a spin-on technique, CVD, or another method. There were approximately 15 main companies involved in this type of materials R&D and manufacturing during our period of analysis, though today Applied Materials dominates the current market with their Black Diamond type materials.
- *Equipment Suppliers*: Makers of CVD, spin-on, and X-ray equipment. During our period of analysis, two primary firms—Jordan Valley Semiconductor [JVS] and BEDE—were involved in producing X-ray equipment, and two others—Novellus and

Applied Materials—dominated the market for CVD and spin-on equipment. Today, JVS has acquired BEDE, creating the dominant X-ray equipment manufacturer, and Novellus and Applied Materials are still the main suppliers of CVD and spin-on equipment.

- *Device Manufacturers*: Manufacturers of ICs. Device manufacturers were the most affected group as they were trying to identify suitable low-k materials to integrate into their processes as quickly as possible. Many different types of semiconductor devices will likely utilize low-k materials in the future, but this study focused on those manufacturers who directly benefited from NIST's research, including mainly the six largest IC manufacturers.

Table 3-2 shows employment and sales information for the main companies in each stakeholder group that were or are involved in low-k materials research in some way. These three groups represent the principal supply chain for the production and use of low-k materials.

With the assistance of Christopher Soles, Eric Lin, Barry Bauer, and Wen-li Wu at NIST, efforts were made to identify an individual at each company who could speak to the impact of NIST's low-k research and who would be willing to talk with RTI about the dimensions of the economic impact of the data and techniques NIST developed. Representatives of 13 companies were willing to participate in RTI's data collection efforts. These companies span all three segments of the supply chain: five materials suppliers, four equipment suppliers, and four device manufacturers.

Table 3-3 provides estimates of market coverage of data collected during interviews.[11] The "market" for each stakeholder group was defined by expert and stakeholder estimates of the sales of low-k materials by materials suppliers; sales of X-ray, CVD, and spin-on equipment by equipment suppliers; and research on and planned use of low-k materials by device manufacturers. Secondary information and expert interviews were used to verify market sizes for each stakeholder group. The relationship between information in Tables 3-2 and 3-3 is purposely not defined to prevent identification of companies that participated in RTI's interviews.

[11] RTI prepared and used an interview guide to facilitate the interviews. See Appendix B.

Table 3-2. Stakeholders' Sales and Employment Data, by Company

Company	Company Sales (2007 $million)	Employment
Materials Suppliers		
Air Product and Chemicals Inc.	$10,038	22,100
Applied Materials[a]	$9,735	15,328
ASM International[a]	$11,407	11,832
Dow Chemical	$53,513	45,856
Dow Corning	$4,392	9,000
Dupont	$30,653	60,000
Honeywell	$34,589	122,000
JSR	$2,876	4,576
Novellus[a]	$1,570	3,698
Rohm and Haas[b]	$8,897	15,710
Equipment Suppliers		
X-ray Equipment Suppliers		
Jordan Valley Semiconductor[c]	NA[d]	NA[d]
Technos	NA[e]	NA[e]
CVD and Spin-on Equipment Suppliers		
Applied Materials[a]	$9,735	15,328
ASM International[a]	$11,407	11,832
Novellus[a]	$1,570	3,698
Semitool	$215	1,157
Device Manufacturers		
AMD	$6,013	16,420
IBM	$98,786	426,969
Intel	$38,334	86,300
Freescale	$5,622	23,200
Spansion	$2,501	9,300
TI	$13,835	30,175

[a]These companies are materials suppliers and suppliers of CVD equipment.

[b]Rohm and Haas acquired Shipley, a major chemical and materials supplier, in 1999, combining two of the largest materials suppliers in the industry.

[c]Jordan Valley Semiconductor purchased BEDE, another major X-ray equipment manufacturer, in April 2008, making it the dominant manufacturer of X-ray technology equipment.

[d]Based in Israel, Jordan Valley Semiconductor is a privately-held company, ownership of which is split among several large holding companies and investment groups. Financial and employment data is unavailable.

[e]Technos International is owned by Technos Co. Ltd. of Japan. Financial and employment data is unavailable.

Source: Hoover's Inc.

Table 3-3. Market Coverage of Relevant Stakeholders Participating in Interviews

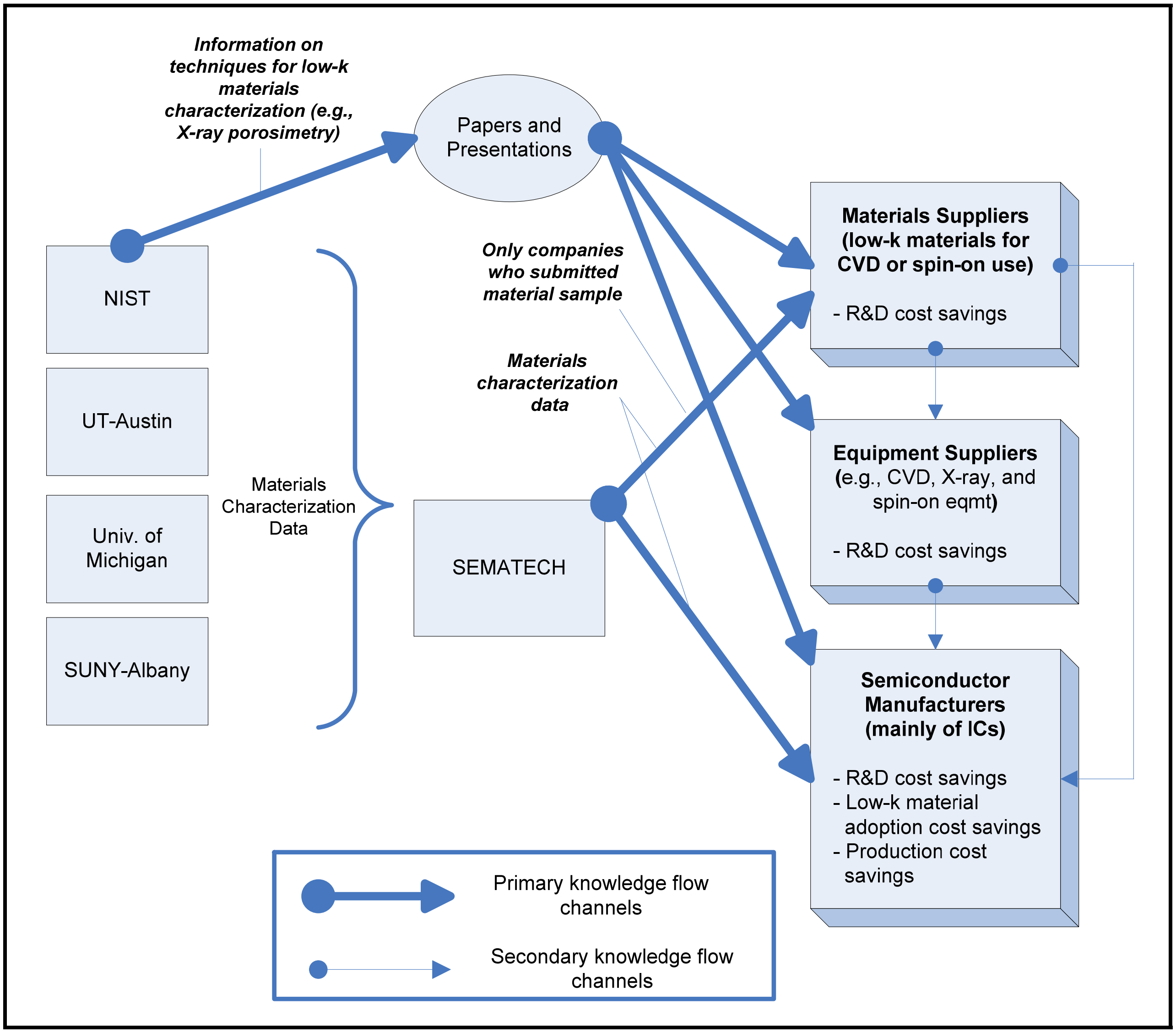
Stakeholder Group	Number of Firms	Approximated Market Share Represented
Materials Suppliers	5	80%
Equipment Suppliers		
X-ray equipment	2	90%
CVD and spin-on equipment	2	95%
Device Manufacturers	4	80%

3.3 THE COUNTERFACTUAL SCENARIO

The counterfactual evaluation method is the appropriate method for evaluating a publicly funded, publicly performed research project. NIST's research on low-k materials characterization clearly fits in this domain. The evaluation question asked when using the counterfactual evaluation method for this study was: What would the private sector have invested in the absence of the public sector's research funding support, and how would the research/production outcomes differ from what actually occurred? The answer to this two-part question illustrates the benefits of the public's investments—namely, the costs saved or avoided by the private sector and other benefits such as quality improvements. This approach also sought to determine whether the publicly funded research (1) provided a unique capability—a result otherwise not possible or unlikely to occur (e.g., because private entities would not have been able to see a sufficiently positive private return on investment)—or (2) accelerated development and deployment of low-k materials.

Figure 3-1 conceptualizes the knowledge flows associated with the impact of NIST's research on low-k materials characterization. The thicker lines show linkages between NIST and the direct beneficiaries. Thinner lines indicate where knowledge flows were less direct. The figure shows how NIST and other organizations performed research and provided the resulting data to SEMATECH who distributed this information to their membership, which was comprised of the largest device manufacturers in the industry. NIST also developed novel techniques for low-k materials characterization. They disseminated information both on their techniques—procedural information and accuracy analyses—and on general results from materials analysis to the industry through papers written by and presentations given by NIST technical staff.

Figure 3-1. Primary and Secondary Knowledge Flows of NIST Low-k Research



This study focused on how firms would have acted without these knowledge flows. According to interviews with industry stakeholders, NIST provided two key contributions: (1) materials characterization *data* and (2) new low-k materials characterization *techniques* (e.g., X-ray porosimetry). Without these, stakeholders in all three groups indicated that costs would have increased. Broadly, RTI's analysis concluded that NIST's work led to the following categories of industry cost savings:

1. reduced R&D costs,
2. reduced low-k adoption costs, and
3. reduced production costs.

Interviews suggested that without NIST the industry would have still moved toward adopting low-k materials. However, without NIST's involvement in low-k materials characterization, interview participants did not believe that the industry would have tried a radically different approach—for example, accelerating the use of "air gaps" in materials[12] or moving faster toward the use of 3-D architectures in chip design and production.[13] Instead, the characterization of low-k materials would have been much more costly without NIST.

Low-k characterization work would have been duplicative (spread among many firms), multiplying total industry costs. Further, data would likely have been of lower quality; NIST used characterization techniques, such as X-ray porosimetry, that were much more accurate than techniques being used by the industry at the time, resulting in higher quality data being available than if the industry had proceeded without NIST.

A key assumption in the counterfactual scenario for modeling economic impacts was that advances in chip performance would have proceeded (and will continue to proceed) along the same timeline outlined in the industry's Roadmap in the absence of NIST's activities. Thus, this analysis holds the quality of related final products and services unchanged, and the impact of NIST's contributions is primarily to lower the costs throughout the product life cycle as described in the impact categories 1 through 3 above.

According to interviews, NIST's primary contribution was to develop effective characterization techniques and to create and disseminate objective data that reduced the industry's R&D cost savings. As a result of the highly complex nature of such work and the proprietary status of

[12] IBM has developed what they refer to as "air gap" technology to improve the insulation within semiconductor devices. IBM's process involves making a chip that is essentially hollow inside. This requires production in a high vacuum environment and thus, some experts believe it will be too expensive for large-scale production. A May 2007 press release from IBM described their technology as follows: "This new form of insulation, commonly referred to as 'air gaps' by scientists, is a misnomer, as the gaps are actually a vacuum, absent of air. The technique deployed by IBM causes a vacuum to form between the copper wires on a computer chip, allowing electrical signals to flow faster, while consuming less electrical power. The self-assembly process enables the nano-scale patterning required to form the gaps; this patterning is considerably smaller than current lithographic techniques can achieve." (http://www-03.ibm.com/press/us/en/pressrelease/21473.wss) IBM has indicated plans to begin manufacturing servers based on this technology in 2009.

[13] 3-D architecture refers to using vertical dimensions and horizontal dimensions fully when developing chip design. 3-D ICs have the potential to eliminate signal delays and power consumption caused by horizontal wiring lengths — either on or between chips. As such, they offer the potential to lead to "dramatically improved performance at a much lower cost than building a new leading-edge, 45, 30 or 22 nm transistor fab," according to an August 2007 article in Semiconductor Magazine (http://www.semiconductor.net/article/CA6462379.html).

such research within private companies, the involvement of a standing research organization such as NIST was irreplaceable by the industry. Academic researchers could have provided some of the same data, as could other research organizations such as SEMATECH and IMEC[14], but NIST offered the highest quality and most expedient data possible to a large portion of the industry.

Quantitative estimates were calculated for the impact of NIST's work in terms of R&D cost savings—i.e., on materials characterization research. Additional benefits, such as the impact of NIST's work on materials adoption costs and production costs, as well as improvements in product quality, are discussed qualitatively.

3.4 NIST RESEARCH COSTS

Soles, Lin, and Wu at NIST estimated NIST's costs undertaken between 1998 and 2006 on low-k materials research. SEMATECH paid NIST to conduct low-k materials analysis between 1998 and 2006, and NIST supplemented this funding out of its own budget to conduct additional work developing characterization techniques and advanced processes. Table 3-4 shows the total spending by NIST ($3.9 million) broken out between SEMATECH funding ($1.2 million) and NIST internal funding ($2.7 million).

NIST's materials characterization data were transferred to SEMATECH at a rate of approximately 15 to 20 material samples per year. Through targeted industry interviews, RTI estimated the level and timing of the use of these data and the effect they had on industry companies in terms of reduced R&D costs—that is, cost savings from avoided or duplicative research. SEMATECH indicated that approximately 10 semiconductor device manufacturers working on low-k materials research received their periodic summaries of characterization results.

[14] Interuniversity Microelectronics Centre (IMEC) is a micro- and nano-electronics research center located in Leuven, Belgium.

Table 3-4. NIST Research Costs Relating to Low-k Characterization ($2008)

Year	SEMATECH Funding	NIST Internal Funding	Total NIST Research Investment
1998	$47,343	$—	$47,343
1999	$99,712	$393,864	$493,576
2000	$116,037	$360,326	$476,363
2001	$179,315	$407,044	$586,359
2002	$175,696	$522,403	$698,099
2003	$172,113	$423,399	$595,512
2004	$224,285	$231,013	$455,298
2005	$162,867	$277,960	$440,827
2006	$26,802	$79,936	$106,738
Total	$1,204,170	$2,695,944	$3,900,115

Note: Real ($2008) costs were calculated using the seasonally adjusted Gross Domestic Product Implicit Price Deflator (2,000 = 100), U.S. Department of Commerce: Bureau of Economic Analysis, http://research.stlouisfed.org/fred2/data/GDPDEF.txt.

3.5 QUANTITATIVE PRIVATE SECTOR BENEFITS

The availability of NIST's data enabled materials suppliers, equipment suppliers, and device manufacturers to focus on comparing a handful of low-k materials and testing integration issues as opposed to developing basic materials characterization information, a very labor-intensive, time-consuming process at which few firms were expert. Without NIST, at least a dozen firms would have each replicated some portion of NIST's data characterization research for at least 2 to 3 years; however, because of the technical complexity and cost involved, most would not have performed even half the number of materials analyses that NIST did. Using information collected during interviews on the exact timing of cost savings and the alternative spending that would have occurred, RTI developed benefits estimates.

Device manufacturers were the most directly affected by NIST's work; on average, RTI interviews suggest that each of the top five IC manufacturers would have each increased R&D spending by more than $2.5 million without NIST's research between 1998 and 2006. Other manufacturers would have increased their spending by smaller amounts. As a share of R&D investment in low-k materials characterization, this represents almost half of all spending.

Materials suppliers also saved significant R&D resources. RTI interviews suggest that four of the largest materials suppliers would have each increased R&D spending by more than $1 million between 1998 and 2006 if NIST had not conducted their research. NIST's data provided high quality characterization feedback that particularly benefited materials suppliers conducting robust analysis of materials properties aimed at developing a better understanding of the properties of their products.

The top two equipment suppliers would likely have spent over $1.5 million each between 1998 and 2006 without NIST's involvement. These equipment suppliers were conducting research aimed at understanding materials in order to support the development of equipment for producing ICs. Other equipment manufacturers, including suppliers of X-ray equipment, indicated that they likely saved some money based on NIST's work, but they were unable to quantify these savings.

Table 3-5 provides estimates of the cost savings that accrued to interview participants based on the characterization data that NIST provided. The cost savings benefits presented are only those described directly by interview participants. Extrapolated industry-wide benefits are presented and discussed in Chapter 4. Of note, interview participants indicated that their cost to adopt or make use of NIST's data was negligible.

Table 3-5. Private-Sector R&D Cost-Savings Benefits: Base Case ($2008)

Year	Real Cost-Savings Benefits
1998	$241,764
1999	$883,148
2000	$1,049,211
2001	$1,369,407
2002	$1,494,860
2003	$1,250,607
2004	$1,095,317
2005	$883,441
2006	$125,000
Total	$8,392,755

3.6 QUALITATIVE BENEFITS

In addition to the reported R&D cost savings or costs avoided that RTI estimated based on information provided during interviews with company representatives, RTI formulated additional qualitative information relevant to the social benefits associated with NIST's research. Broadly, NIST's work had the following impacts:

1. accelerated the availability of robust low-k materials characterization data (product acceleration benefit),
2. freed up R&D resources for other innovation activities, (quality improvement benefit), and
3. provided new low-k materials characterization processes (cost savings and quality improvement benefit).

Quantitative analysis of these benefits was not possible. Relevant information on the impacts was not documented by industry in "real-time" when NIST research and results were being utilized, and as such, more complex benefits could not be estimated by industry members.

3.6.1 Accelerated the Availability of Low-k Data

Interview participants indicated that without NIST's work, the overall characterization of low-k materials would have slowed, likely by at least 2 or 3 years. NIST played a critical role in determining the strengths and weaknesses of various materials characterization techniques, which led directly to the rapid development of a robust set of objective characterization data.[15] However, no interview participants were able to value the impact of low-k materials data being available more quickly. As stated above, RTI's analysis assumed that product availability timelines would not have changed without NIST's involvement; however, if products using low-k materials were available sooner, the economic impact in terms of the use of more advanced products would have been significant.

3.6.2 Enabled Innovative Research

NIST's work enabled manufacturers to periodically focus on a handful (e.g., two or three) of low-k materials that met a sufficient number of process characteristics based on data provided by SEMATECH's program, rather than analyzing a dozen or more materials at a basic

[15]Over the years, other organizations and methods began to mature and became competitive with NIST. For example, IMEC developed EP techniques for on-wafer gas absorption pore characterization. However, without NIST, interviews indicated that the SEMATECH materials characterization efforts would likely have been delayed by 2 to 3 years or the resulting data would have been of much lower quality.

level. As such, according to several semiconductor manufacturers, NIST's work enabled more innovation in R&D to occur. Without NIST, manufacturers would have likely focused significant attention on the development of new characterization techniques and the analysis of dozens of materials. Instead, they were able to shift resources to activities that involved more innovative research.

3.6.3 Provided New Materials Characterization Techniques

NIST developed a variety of novel techniques for materials characterization, the specific impact of which was not quantified. During NIST's research, particularly in the first 2 or 3 years, NIST developed and modified several techniques for measuring materials properties; these techniques likely improved both the cost of measurement and the quality of products downstream from their use. NIST's main contributions included using

- X-ray reflectivity techniques for porosity analysis of low-k materials (i.e., X-ray porosimetry), and
- composition techniques (ion beam scattering and recoil) for testing the elemental content of low-k materials.

NIST was the first organization to apply X-ray reflectivity to low-k materials porosity analysis. Although they did not invent the technique, NIST realized that they could use X-ray reflectivity for low-k films to quantify porosity and test other material characteristics. JVS, an equipment manufacturer, came to NIST for a demonstration of NIST's technique and subsequently developed an application of X-ray techniques for low-k materials that improved measurement speed from 2 hours (for NIST's process) to less than 1 minute.

As described above, NIST's use of X-ray reflectivity resulted in higher quality data than would have otherwise been possible; however, study interviews suggest that industry adoption of the X-ray technique was limited. Although X-ray porosimetry provides higher quality data than alternate techniques, such as EP or PALS, X-ray reflectivity in its current form is a costly procedure as compared to EP. As such, EP has been adopted by stakeholders and is used more often than X-ray porosimetry for analysis of materials' pores. Yet, without NIST's involvement, interviews suggested that the use of X-ray for low-k materials analysis today would be even lower, and the value of NIST's data would have been reduced. Had EP not become a more cost-effective, relatively quick technique, X-ray porosimetry would likely have been adopted by more companies.

X-ray porosimetry is also the most likely technique to be considered in future production environments. Currently, manufacturers are uncertain whether they will need to measure porosity within a fab, which they would prefer not to do because of the cost. However, as chip feature sizes continue to decrease, real-time porosity analysis may become necessary. If so, X-ray porosimetry is the most likely porosity characterization technique to be used in the fab.

NIST also used composition techniques such as ion beam scattering to quantify the hydrogen, silicon, carbon, oxygen, and nitrogen content of materials. Backing out the atomic composition was required because the samples were provided to NIST through SEMATECH without any compositional information. As mentioned before, all materials tests were conducted blind.

Using NIST's measurement methodologies and materials characterization data, many companies in the industry perfected their own characterization processes during the early 2000s. As discussed in Chapter 2, NIST also published an X-ray porosimetry recommended practice guide (Soles et al., 2004), which is available on NIST's Web site and has also been given out at industry workshops and conferences. According to NIST's records, the online version of the guide has been downloaded 927 times between 2006 and 2008. Unfortunately, accurate download statistics are not available for 2004 through 2005 because of a change in the NIST Web site infrastructure. NIST estimated that the Web page with the URL for the downloadable PDF was accessed over 5,000 times between 2004 and 2005, but the actual number of successful downloads cannot be verified. Another 20 or so industry researchers have been mailed hard copies of the guide after submitting requests to NIST.

NIST also published seven papers and one book chapter (listed in Appendix A) that NIST indicated were at least partially based on their low-k materials characterization research. These publications showed the usefulness of their X-ray technique for low-k materials porosimetry and presented information on materials characterization results from methods including neutron scattering and positron annihilation lifetime spectroscopy. Non-author citation counts, year-by-year and cumulative, are presented in Table 3-6. By 2007, these eight publications had been

Table 3-6. Non-Author Citations to Primary Relevant Publications, by Year

Year	Number of Papers Published (Month of Publication)	Citations	Cumulative Citations
2000	2 (February, July)	1	1
2001	2 (April, May)	12	13
2002	2 (July, December)	21	34
2003	1 (February)	19	53
2004	1 (July)	31	84
2005		25	109
2006		32	141
2007		18	159
2008		4	163

Note: Citations in 2008 are through June 21. The December 2002 publication was a book chapter. All other publications in this Table were in peer-reviewed journals.

cited a total of over 160 times by other researchers in peer-reviewed journal articles.

In summary, NIST's work provided R&D and production benefits in the form of cost savings and quality improvements. Some R&D cost savings were quantified; others, such as the impact on the adoption costs for low-k materials, were not. Further, NIST's work likely accelerated the use of low-k materials and improved the quality of products being developed, resulting in higher production yields and/or better products.

4 Measures of Economic Return

RTI developed extrapolated benefits estimates that provide a more comprehensive view of the impact of NIST's research on R&D cost savings. RTI also calculated two traditional evaluation metrics relevant to this study: the benefit-to-cost ratio (BCR) and net present value (NPV). This chapter discusses the extrapolation method used and the resulting benefits estimates, as well as a presentation of the evaluation metrics for each case.

4.1 EXTRAPOLATING BENEFITS

Table 4-1 is a summary of the real cost data in Table 3-4 and the interview benefit data in Table 3-5. These benefits are only those estimated by the 13 companies whose representatives RTI interviewed. As such, the benefits in Table 4-1 are lower-bound estimates. Still, these conservative estimates indicate that, from a social perspective, NIST's investments in low-k research were worthwhile.

In order to provide estimates of the total industry benefits, RTI extrapolated from the base case figures. Based on explicit company impact estimates and information on total market sizes by stakeholder group provided during interviews, RTI developed the market share represented by base case estimates. RTI then developed two types of extrapolation estimates.

First, RTI developed a full extrapolation of benefits. These estimates were calculated in the following way: if, for example, the cost-savings benefits to companies representing 80% of the market are $100 (base case), then cost-savings benefits to the industry are $100/.80 or $125

Table 4-1. NIST Research Costs and Private-Sector R&D Benefits: Base Case ($2008)

Year	Real Cost	Real Cost-Savings Benefits
1998	$37,500	$241,764
1999	$396,000	$883,148
2000	$390,000	$1,049,211
2001	$490,500	$1,369,407
2002	$596,000	$1,494,860
2003	$519,000	$1,250,607
2004	$406,000	$1,095,317
2005	$406,000	$883,441
2006	$101,500	$125,000
Total	$3,342,500	$8,392,755
NPV	$2,555,799	$6,486,258

(fully extrapolated case). These fully extrapolated benefits are shown in the fourth column of Table 4-2. Total benefits equaled almost $30.5 million, with an NPV of approximately $23.7 million.

Second, RTI used a 50% extrapolation (i.e., the average of the benefits in the third and fourth columns of Table 4-2). The 50% extrapolated case estimates are shown in the fifth column in Table 4-2. Total benefits equaled close to $20 million, or an NPV of approximately $15 million. These estimates provide more conservative industry-level estimates than the full extrapolation case.

Of note, the market coverage data provided in Table 3-3 were not used for extrapolation purposes. These data represent the market coverage of companies that participated in interviews and provided *either* quantitative or qualitative information, but not necessarily both. Market share data used to develop extrapolation estimates are not provided in order to protect company-level information that was provided during interviews.

Table 4-3 provides benefits by stakeholder group for the fully extrapolated case in order to prevent revealing company-specific data. As can been seen, device manufacturers received the vast majority of the benefits with over $22 million accrued. This is as expected, since interviews suggest that manufacturers were spending the most time trying to characterize many different low-k materials and find ones that would be suitable to meet production needs. Industry stakeholders

Table 4-2. NIST Research Costs and Private-Sector R&D Benefits: Base Case and Extrapolated Cases ($2008)

Year	Real Cost	Real Cost-Savings Benefits	Real Cost-Savings Benefits: Fully Extrapolated	Real Cost-Savings Benefits: 50 Percent Extrapolated
1998	$37,500	$241,764	$967,056	$604,410
1999	$396,000	$883,148	$3,100,133	$1,991,640
2000	$390,000	$1,049,211	$3,874,158	$2,461,685
2001	$490,500	$1,369,407	$5,181,765	$3,275,586
2002	$596,000	$1,494,860	$5,612,297	$3,553,579
2003	$519,000	$1,250,607	$4,573,384	$2,911,995
2004	$406,000	$1,095,317	$3,786,942	$2,441,129
2005	$406,000	$883,441	$3,149,187	$2,016,314
2006	$101,500	$125,000	$250,000	$187,500
Total	$3,342,500	$8,392,755	$30,494,923	$19,443,839
NPV	$2,555,799	$6,486,258	$23,650,492	$15,068,375

Table 4-3. R&D Benefits Estimates by Stakeholder Group ($2008)

Stakeholder Group	Value Based on Full Extrapolation of Benefits
Materials Suppliers	$4,875,000
Equipment Suppliers	$3,451,096
Device Manufacturers	$22,168,827
Total	$30,494,923

indicated that they would have conducted any research needed to stay on track with the industry Roadmap. Materials suppliers received almost $5 million, and equipment suppliers observed approximately $3.5 million in cost-savings benefits. Working in supportive roles to the device manufacturers, both of these groups would have made additional R&D investments to stay competitive.

4.2 DESCRIPTION OF EVALUATION METRICS

Three traditional evaluation metrics are routinely used to evaluate investments: BCR, NPV, and internal rate of return (IRR). BCR and NPV calculation steps are discussed below. No IRR was calculated for the base or extrapolated cases because net benefits are positive in all years.[16]

The BCR calculated in this analysis is the ratio of the NPV of benefits to the NPV of costs, which accounts for differences in the timing of cash flows (which has implications for the real value of $1 in one time period versus another).

The BCR uses the annual time series of quantified benefits derived from the efficiency gains. Letting B_t be the benefits accrued in year *t* by firms and letting C_t be the total costs for the project in year *t* by firms and industry consortia, then the BCR for the program is given by

$$(\text{BCR}) = \frac{\sum_{i=0}^{n} \frac{B1_{(t+i)}}{(1+r)^i}}{\sum_{i=0}^{n} \frac{C_{(t+i)}}{(1+r)^i}} \qquad (4.1)$$

where

t is the first year in which benefits or costs occur,

n is the number of years the benefits and/or costs occur, and

r is the social discount rate.

In this study, *r* was set at 7%, which is the Office of Management and Budget (OMB)-specified level.[17] Because benefits and costs occur at different time periods, both are expressed in present-value terms before the ratio is calculated. Essentially, a BCR greater than 1 indicates that quantified benefits outweighed the calculated costs. A BCR less than 1 indicates that costs exceeded benefits, and a BCR equal to 1 means that the project broke even.

[16] The IRR metric is usually presented in investment analyses. The IRR can be interpreted as the percentage yield on an R&D project over the life of the project, often multiple years (Tassey, 2003). In mathematical terms, the IRR is the value of *r* that sets the NPV equal to zero in Equation (4-2) or results in a BCR of 1 in Equation (4-1). The IRR's value can be compared with conventional rates of return for comparable or alternative investments. Risk-free capital investments such as government bonds can be expected to yield rates of return under 5% in real terms, while equities seldom return more than 10% over an extended period of time. However, in academic studies of the diffusion of new technologies, real rates of return of 100% or more have been found for significant advances with broad social benefits. It should be noted that in cases for which costs exceed benefits or if net benefits are all positive or all negative an IRR cannot be calculated. Also, time series with inflexion points prohibit the use of this measure by yielding multiple solutions (Tassey, 2003).

[17] See OMB Circular A-94.

The NPV of the investment in a project is calculated as

$$NPV = \sum_{i=0}^{n} \left[\frac{B1(_{t+i})}{(1+r)^i} - \frac{C(_{t+i})}{(1+r)^i} \right], \qquad (4.2)$$

where the terms have the same meanings as identified for Equation (4.1). Any project that yields a positive NPV is considered economically successful. Projects that show a positive NPV when analyzed using OMB's 7% real discount rate are socially advantageous. A negative NPV would indicate that the costs to society outweigh the benefits, and an NPV equal to zero would indicate a breakeven point.

4.3 EVALUATION ANALYSIS: BASE CASE AND EXTRAPOLATED CASES

The data in Table 4-1 and 4-2 are the basis for the calculations of the evaluation metrics in Table 4-4. Based on data collected explicitly during interviews (base case), NIST's research resulted in net benefits of approximately $5 million with an NPV of almost $4 million. The BCR is 2.54.

The two alternative cases provide more probable metrics by which to gauge the cost-savings impact of NIST's investments. The full extrapolation resulted in calculated net benefits of over $27 million and an NPV of approximately $21 million. The BCR was 9.25. The partial (50%) extrapolation is a more conservative estimate of the cost-savings benefits accrued by the industry. The partial extrapolation net benefits were approximately $16 million with an NPV of over $12.5 million. The BCR for the partial extrapolation was 5.90.

Table 4-4. Evaluation Metrics: Base Case and Extrapolated Cases

Metric	Value Based on Interview Data	Value Based on Full Extrapolation of Benefits	Value Based on 50% Extrapolation of Benefits
Costs ($2008)	$3,342,500	$3,342,500	$3,342,500
Benefits ($2008)	$8,392,755	$30,494,923	$19,443,839
Net Benefits ($2008)	$5,050,255	$27,152,423	$16,101,339
Benefit-to-Cost Ratio	2.54	9.25	5.90
Net Present Value ($2008)	$3,930,459	$21,094,692	$12,512,576

5 Conclusion

In this study, RTI quantified the impact of NIST's low-k characterization program on the R&D portion of the semiconductor industry. The values of the evaluation metrics in Table 4-4 clearly indicate that NIST's investments in low-k characterization, exemplified by the materials data generated and the characterization techniques developed, have had a significant positive social return.

The fully extrapolated benefits calculation shows that NIST's investments resulted in approximately $27 million of net benefits and an NPV of $21 million. These calculations represent what the industry would have spent in the absence of NIST's research and findings less NIST's costs. Industry stakeholders indicated that they would have conducted extensive duplicative efforts. No single organization would have developed the quantity or quality of data developed by NIST. As such, the industry observed R&D cost savings, as well as quality improvements that were reported but not estimated quantitatively by stakeholders.

RTI's calculated benefits may be considered conservative for several reasons and thus may understate the social benefits associated with NIST's research in low-k. First, R&D cost savings are just one of the benefits that resulted from NIST's knowledge flow chain (see Figure 3-1). NIST's research likely had a significant impact on the cost to adopt low-k materials. As an example, in the early 2000s, some device manufacturers were planning to incorporate low-k materials into new manufacturing facilities based on limited information on low-k materials and related processes; however, the data provided by NIST and others working with SEMATECH helped to prevent the adoption of certain materials. In some cases, companies changed their facility plans, potentially resulting in significant cost savings.

NIST's work likely also enabled faster time to market of ICs with low-k materials, such as Applied Materials' Black Diamond, resulting in lower production costs to meet performance requirements for IC manufacturers. Without NIST's work, manufacturers would have had to approach meeting such milestones (as laid out in the industry Roadmaps) by either spending more money on intra-company low-k materials characterization efforts or by other means such as accelerating the use of 3-D architecture techniques that are still being developed. Several stakeholders indicated that the data characterization work conducted by NIST was particularly valuable because the marginal cost of conducting such analyses on a smaller scale (i.e., by an individual company) can be prohibitively high. In particular, investment costs for equipment prevent some companies from conducting more robust analysis (e.g., with X-ray techniques).

The discovery of several important characterization techniques by NIST researchers, between 1998 and 2000, also provided an unquantified benefit. In particular, NIST used X-ray porosimetry to develop high quality materials characterization data between 1998 and 2006.[18] NIST communicated the details of their new technique through journal articles, conference presentations, and a NIST-sponsored recommended practice guide (Soles et al., 2004). Although X-ray porosimetry was not adopted at a high level by the semiconductor industry based largely on the equipment cost, stakeholders indicated that NIST's work on X-ray techniques was very useful to the industry.

Further, several stakeholders indicated that X-ray reflectivity could play a larger role in the future if at future technology nodes low-k materials porosity needs to be analyzed *in situ*. Although today such use is merely speculation, research into the use of X-ray techniques *in situ* could provide significant benefits to the industry. RTI's analysis suggests that NIST might have a role in conducting such research in the future, as well as research aimed at reducing the cost of X-ray porosimetry.

[18] NIST's work on X-ray techniques was based largely on previous work by NIST researcher Wen-li Wu (1993, 1994).

5.1 OBSERVATIONS FOR NIST

During RTI's interviews, participants were asked to offer feedback to NIST. Most discussed the unique role that NIST played and cited one or more of the following as key factors: (1) NIST's objectivity, (2) NIST's extensive technical capabilities (including X-ray and neutron technology), and (3) the centralization of work at NIST. NIST was credited with helping the industry save significant research costs and with accelerating characterization research at a faster pace than would have occurred otherwise.

Two changes in NIST's research and approach were suggested by several participants. First, several manufacturers commented that they wish NIST had continued to conduct materials characterization research in a "turn the crank" fashion. Each manufacturer who offered this feedback noted that NIST had (and still has) unique capabilities in X-ray and neutron analysis, among others, and that some firms were unable to find such capabilities elsewhere or could only find them at a much higher cost.

Further, both manufacturers and equipment suppliers mentioned that NIST could have done more to help with the transfer of its X-ray porosimetry technique out of the lab and into the market as a product. Although NIST wrote a recommended practice guide for X-ray porosimetry, which is published on its Web site, industry members indicated that in order to use NIST's technique a company would need both adequate monetary resources—approximately $100,000 for equipment and labor—and a person with a "very high level of mechanical aptitude." With such resources and skills, a company could retrofit an X-ray reflectivity device for porosimetry analysis in a matter of months.

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Appendix A:
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Appendix B: Interview Guide

The Impact of NIST's Low-k Materials Characterization Research

Interview Instrument

Thank you for your participation in this brief but important survey intended to collect information on the impact of NIST's research developing low-k materials characterization data and new characterization techniques for the semiconductor industry. RTI International will use the results of this survey as part of a research study commissioned by the National Institute of Standards and Technology (NIST). This study will provide an economic impact assessment of the value of NIST's research on low-k materials in support of the U.S. semiconductor supply chain.

Instructions:

This survey should take approximately 15 minutes to complete. Your participation is voluntary, and your responses will be kept strictly *confidential*.[1] You do not need to look up any information; simply provide answers based on your best knowledge and recollection.

[1]**Nondisclosure policy:** RTI has a well-established practice of dealing with confidential information as part of numerous projects. Any information we obtain through these surveys will be used solely in aggregate with other information garnered from other respondents. In no instance will specific individuals or organizations be identified by name in any reports or as part of information that is released publicly or to the National Institute of Standards and Technology based on our discussions.

PART I: General Information

1. Is your parent company based in the U.S.?
   - ☐ Yes
   - ☐ No

2. Is the facility where you personally work located in the U.S.?
   - ☐ Yes
   - ☐ No

3. What is your title? ________________________

4. What semiconductor supply chain group do you represent? [*NOTE*: If you work for a company that has activities in more than one area of the industry supply chain, please select only the group with which you are most knowledgeable. Then, please forward this survey link to an appropriate person for each of the other areas and ask them to fill out a separate questionnaire for that activity.]
   - Integrated circuit designer
   - Materials supplier
   - Equipment supplier
   - Software supplier
   - Front-end processing (wafer fabrication)
   - Back-end processing (packaging, assembly, and test)
   - Other (_______________________________)

5. What main products does your company produce within the group indicated in Question 4 that uses low-k materials research knowledge? _______________________________

6. Approximately, how many employees currently work at your company? ___________

7. Estimated revenues:
   a. What were the approximate gross sales of your company in the most recent fiscal year? _________
   b. Approximately what percentage of these sales is attributable to the *group* that conducts low-k materials analysis? (If you are responding for the entire organization, enter 100%.) _________
   c. Approximately what percentage of these sales (using the answer to Question 7.b. as a reference point) is related to sales of semiconductor products or products to the semiconductor industry? _______

PART 2: Use of SEMATECH/NIST Low-k Materials Characterization Data

1. What do you know about SEMATECH's low-k materials characterization data that were disseminated between 1998 and 2006?

   ____

   ____

2. How did you use the data SEMATECH disseminated?

   ____

   ____

3. During what years and at what level did you use SEMATECH's data?

   ____

4. What benefits did you observe from using SEMATECH's data? (That is, how did costs for R&D, the adoption of low-k materials, and production costs differ based on the availability of SEMATECH's materials characterization data?) The following table provides some broad potential benefit descriptions.

Benefit Description	Benefit Type	Primary Beneficiaries
Decreased materials characterization effort resulting from using NIST data	• R&D cost savings • Adoption (low-k material) cost savings	• Materials suppliers • Equipment suppliers • Device manufacturers
Cost savings from not using faulty/costly materials processes into new fabs	• Adoption (low-k material) cost savings • Production cost savings	• Device manufacturers

   a. R&D cost savings: ______________________

   b. Low-k materials adoption cost savings: ____________________

   c. Production cost savings: ______________________

5. Did you observe any significant adoption costs as part of this process?

   ____

6. What work were you doing on low-k materials characterization between 1995 and 2000?

   ____

7. What would you have done differently in the absence of this data?

   ____

   ____

8. Are you aware that NIST was involved in developing this data? _________

   a. If so, what role do you believe that NIST had? ____ (provide information as necessary)

   b. What portion of the benefits described above should be attributed to NIST's involvement in this research? ____________________________

PART 3: Use of NIST-Identified X-ray Reflectivity (or Porosimetry) Technique for Analysis of Low-k Materials

1. Do you use X-ray reflectivity for low-k materials characterization (also known as porosimetry)? ______________________________

   a. If so, when did you start using X-ray techniques for low-k materials characterization? _______________________________

2. What do you know about NIST's role in helping to identify X-ray techniques for analysis of low-k materials characteristics?

   ____

   ____

3. If possible, please describe how you used NIST's research on X-ray techniques (e.g., based on their published papers and best practice guides)?

   ____

   ____

4. When did you use NIST's research findings?

   ____

   ____

5. What benefits did you observe from using NIST-described X-ray techniques? (That is, how did costs for R&D, the adoption of low-k materials, and production costs differ based on the use of X-ray reflectivity for low-k materials characterization?)

   a. R&D cost savings: _______________________

   b. Low-k materials' adoption cost savings: ______________________

   c. Production cost savings: ________________________

6. What did it cost your firm (e.g., training, new equipment costs, installation costs, downtime) to adopt X-ray techniques as part of your analysis of low-k materials?

   ____

   ____

7. How were you conducting pore analysis of low-k materials prior to using X-ray techniques?

   ____

8. What would you have done differently in the absence of this technique?

   ____

   ____