2-13-95

SANDIA REPORT

SAND93-0349 • UC-404

Unlimited Release

Printed January 1995

Numerical Methods for Determining Interstitial Oxygen in Silicon

J. O. Stevenson, J. W. Medernach

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

Approved for public release; distribution is unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal RD
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Numerical Methods for Determining Interstitial Oxygen in Silicon

J. O. Stevenson and J. W. Medernach
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

The interstitial oxygen (O_i) concentration in Czochralski silicon and the subsequent SiO_x precipitation are important parameters for integrated circuit fabrication. Uncontrolled SiO_x precipitation during processing can create detrimental mechanical and electrical effects that contribute to poor performance. An inability to consistently and accurately measure the initial O_i concentration in heavily doped silicon has led to contradictory results regarding the effects of dopant type and concentration on SiO_x precipitation. We have developed a software package for reliably determining and comparing O_i in heavily doped silicon. The SiFTIR® code implements three independent oxygen analysis methods in a single integrated package. Routine oxygen measurements are desirable over a wide range of silicon resistivities, but there has been confusion concerning which of the three numerical methods is most suitable for the low resistivity portion of the continuum. A major strength of the software is an ability to rapidly produce results for all three methods using only a single Fourier Transform Infrared Spectroscopy (FTIR) spectrum as input. This ability to perform three analyses on a single data set allows a detailed comparison of the three methods across the entire range of resistivities in question. Integrated circuit manufacturers could use the enabling technology provided by SiFTIR® to monitor O_i content. Early detection of O_i using this diagnostic could be beneficial in controlling SiO_x precipitation during integrated circuit processing.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED ✓

MASTER

Acknowledgments

The authors wish to thank Dr. T. R. Guilinger, Dr. M. J. Kelly, and Dr. W. M. Bullis for their critical review of this manuscript. We also thank Siltec Silicon and Charles Evans & Associates for providing traceable oxygen reference wafers and samples analyzed for total oxygen by Secondary Ion Mass Spectroscopy, respectively. This work was performed at Sandia National Laboratories, supported by the U. S. Department of Energy under contract number DE-AC04-94AL85000.

Nomenclature

STM	Standard Test Method
SBT	Short Baseline Technique
CBT	Curved Baseline Technique
SE	Selective Electrochemical
O _i	Interstitial Oxygen
O _p	Precipitated Oxygen
FZ	Float-zone Silicon
CZ	Czochralski Silicon
SIMS	Secondary Ion Mass Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
SiFTIR ®	Interstitial Oxygen Analysis Software
JCAMP	Joint Committee on Atomic and Molecular Physical Data
PS	Porous Silicon
MCT	Mercury Cadmium Telluride
ASTM	The American Society for Testing and Materials
OLD ASTM	ASTM Test Standard F121-79 (9.63)
NEW ASTM	ASTM Test Standard F121-83 (4.90)
DIN	Deutsches Institut für Normung (4.90)
IOC-88	International Oxygen Coefficient 1988 (6.28)
JEIDA	Japan Electronic Industry Development Assoc. (6.06)

Table of Contents

Body

Introduction	1
Experimental Approach	3
O _i Analysis Techniques	4
Standard Test Method (STM)	4
Short Baseline Technique (SBT)	6
Curved Baseline Technique (CBT)	10
Results and Discussion	12
Reproducibility With Well-Resolved Peaks.....	12
Reproducibility With Poorly-Resolved Peaks	13
Results on Lightly Doped Silicon	15
Results on Heavily Doped Silicon	16
Conclusions	18
References	19

Figures

1 SE thinning electrochemical cell	22
2 SE thinning process flow	23
3 PS formation rate	24
4 Typical trans./absorb. spectra	25
5 Trans. determination (STM)	26
6 Baseline comparison (STM, SBT)	27
7 Domain transformation (CBT)	28
8 AC _{peak} determination (CBT)	29
9 AC _{base} determination (CBT)	30
10 Baseline comparison (STM, SBT, CBT)	31

Tables

1 Software Output (STM)	32
2 Software Output (SBT)	33
3 Software Output (CBT)	34
4 Well-Resolved Peaks	35
5 Poorly-Resolved Peaks	36
6 Lightly Doped Silicon	37
7 Heavily Doped Silicon	38

Numerical Methods for Determining Interstitial Oxygen in Silicon

Introduction

The interstitial oxygen (O_i) concentration in Czochralski silicon and the subsequent SiO_x precipitation are important variables in material selection for integrated circuit fabrication. The effects of insufficient or excess gettering are thoroughly discussed in the literature.¹ Uncontrolled SiO_x precipitation during processing can create detrimental mechanical and electrical effects that contribute to poor device performance. Knowledge of the initial O_i concentration is important in controlling the SiO_x precipitation during processing. An inability to consistently and accurately measure the initial O_i concentration has led to confusing and contradictory results regarding the effects of dopant type and concentration on SiO_x precipitation in n+ and p+ silicon.² We present a methodology for rapidly determining and comparing O_i in heavily doped silicon.

The two most common methods for determining oxygen in silicon are Secondary Ion Mass Spectroscopy (SIMS) and Fourier Transform Infrared Spectroscopy (FTIR). Methods other than SIMS and FTIR exist for determining oxygen in silicon, but are usually destructive and less precise.³⁻⁷ SIMS does not resolve O_i from precipitated oxygen atoms (O_p) and must therefore report the sum of the two (i.e. total oxygen content). Since defect densities have been shown to correlate with O_i content and not necessarily with O_p content, SIMS results may not accurately estimate defect densities.

Experimental evidence suggests that the SIMS technique does indeed systematically overestimate oxygen content with respect to the FTIR method.^{8,9} It is difficult, however, to say whether this difference is due entirely to the presence of FTIR inactive oxygen precipitates, or rather can be attributed to systematic errors in the methods.¹⁰ There is, in fact, some evidence that essentially all the atoms reside in interstitial sites rather than in precipitated form in most cases.¹¹ We will, therefore, operate under the generally held belief that essentially all of the oxygen is in interstitial form unless some heat treatment has occurred to cause precipitation.

The O_i concentration is determined from FTIR data using the peak height of the 1107 cm^{-1} band, which arises from the antisymmetric stretch vibration of the O_i species.^{12,13} Routine O_i measurements are desirable over a wide range of silicon resistivities, but the FTIR technique has certain limitations in that regard. The absorption band for the localized Si-O bond is readily detected by FTIR on lightly doped silicon of standard thickness (i.e. resistivity greater than $0.1\text{ }\Omega\text{-cm}$ n-type and $1.0\text{ }\Omega\text{-cm}$ p-type; thickness of $625\text{ }\mu\text{m}$). The O_i content of heavily doped silicon (i.e. resistivity less than $0.1\text{ }\Omega\text{-cm}$ n-type and $1.0\text{ }\Omega\text{-cm}$ p-type) cannot be reliably measured on standard thickness wafers by FTIR transmittance due to the interference from free carrier absorption. The frequency dependence of the free carrier absorption causes significant baseline curvature and shrouds the weak O_i band.^{14,15} As a result, calculations assuming a linear baseline tend to overestimate O_i .¹⁶

Determination of O_i in heavily doped silicon usually employs some form of bulk wafer thinning to reduce free carrier absorption effects and allow FTIR measurement.^{17,18} Thinning is achieved by mechanically lapping or chemically etching an entire wafer to the desired thickness. Double-side polishing is performed in some cases. Bulk wafer thinning has the serious disadvantage of critically altering the entire thickness dimension, thereby precluding additional wafer processing in many instances. Bulk wafer thinning also seriously compromises the structural integrity of the silicon substrate. Certain process lines are incapable of handling such altered wafers.

We have developed a three-step technique for determining O_i in heavily doped silicon: Selective Electrochemical (SE) thinning of a limited area of a wafer, FTIR transmittance measurements on the thinned areas, and O_i analysis of the FTIR spectra using a custom software package. Free carrier absorption effects are reduced by SE thinning so that FTIR transmittance can be measured on the thinned areas. SE thinning in a small area has the advantage of maintaining both the overall thickness dimension and the structural integrity of the silicon substrate, thereby allowing additional wafer processing, if desired. The SE thinning and FTIR processes are discussed in detail in a related publication¹⁹ and reviewed here. We shall, therefore, focus our attention on the FORTRAN software that was written to analyze the FTIR spectra for O_i content.

The SiFTIR® code implements three independent oxygen analysis methods in a single integrated package. The algorithms are founded on equations discussed in the literature.^{8,9,18,20} SiFTIR® is a DOS application that runs on the IBM architecture (386 based machine). The code has also been ported to the VMS operating system on the DEC architecture (VAX based machine). A number of equations in the literature were shown to be very unstable over particular data regimes. A correction for multiple internal reflections was the most glaring numerical instability. Precision was also being lost in many instances. Using well-known mathematical relationships, these ill-behaved equations were reformulated to minimize numerical instabilities and to preserve accuracy that might otherwise be lost. A thorough description of these three methods appears in the O_i analysis techniques section of this document.

Routine oxygen measurements are desirable over a wide range of silicon resistivities, but there has been confusion concerning which of the three numerical methods is most suitable for the low resistivity portion of the continuum. A major strength of the software is an ability to rapidly produce results for all three methods using only a single FTIR spectrum as input. This ability to perform three analyses on a single data set allows a detailed comparison of the three methods across the entire range of resistivities in question. Since SIMS and FTIR results should agree within the experimental error of each method under our belief that essentially all of the oxygen is in interstitial form, we may use SIMS results to gauge the effective range of each of the three numerical methods. Manufacturers of device silicon could use the enabling technology provided by the SiFTIR® code to monitor O_i content prior to device processing. Early detection of O_i using this diagnostic could minimize costly device failure downstream.

Experimental Approach

All silicon wafers used in this study were <100> orientation and 100 mm in diameter with an initial nominal thickness of 625 μm . The study included heavily doped (antimony) n-type silicon, heavily doped (boron) p-type silicon, and lightly doped (boron) p-type silicon. The SE thinning process is an adaptation of porous silicon (PS) formation with a subsequent removal of the PS by a caustic solution. Consequently, this process shares many of the experimental procedures developed for other PS microelectronics applications. At Sandia National Laboratories, the PS process was developed and optimized by Tsao, et al. for heavily doped n-type and p-type silicon layers used in silicon-on-insulator (SOI) device fabrication.^{21,22}

An electrochemical cell used in this study is illustrated in Figure 1. Silicon is made porous by configuring the silicon wafer as the anode, while a platinum mesh is employed as the cathode. The area or areas to be thinned can be defined by an o-ring or by photolithography. The SE thinning process flow is shown in Figure 2. The masking and patterning techniques developed for prolonged etching of silicon in hydrofluoric acid electrolyte has enabled us to progress from o-ring masking to standard microelectronics masking techniques.

The electrochemical cell contains a 1:1 (by volume) mixture of 49% hydrofluoric acid:water or a 1:1 (by volume) mixture of 49% hydrofluoric acid:ethanol. Power is applied using a constant current source with a current density of approximately 80 mA/cm^2 . The type and concentration of dopant, as well as silicon type and resistivity, can affect the PS formation. Under the above experimental conditions, the PS formation rate is 3.1 $\mu\text{m}/\text{min}$ for heavily doped n-type silicon, 3.0 $\mu\text{m}/\text{min}$ for heavily doped p-type silicon, and 2.2 $\mu\text{m}/\text{min}$ for lightly doped p-type silicon. Figure 3 illustrates a typical PS formation rate for heavily doped n-type silicon.²³

On completion, the power is turned off and the wafer allowed to equilibrate for 30 to 60 minutes, depending on the depth of the PS layer. The wafer is then removed from the cell, rinsed in deionized water, and placed into a container with 5M NaOH for the removal of the PS layer. It was observed early in our study that time was required for the wafer to equilibrate after the PS formation to reduce the degree of the energetic reaction which occurs when the wafer is placed into the caustic solution. An alternative approach to removal of the PS layer is to increase the current density by a factor of three to four at the end of the anodization process. This abrupt increase in current density causes most of the PS layer to separate from the wafer. This significantly reduces the degree of the energetic reaction which occurs when the wafer is placed into the caustic solution.

An ADE Model 7000 non-contact wafer inspection system was used to measure thickness at three locations in the SE thinned areas on the wafers. A Nicolet Model 60SX FTIR spectrometer with an MCT detector was used for room temperature transmittance measurements. A resolution of 4 cm^{-1} was used through the 900 to 1300 cm^{-1} frequency range for the O_i determination. SiFTIR® is capable of reading the spectral data from the Nicolet 60SX in a variety of different formats, including X-Y pairs and JCAMP. Traceable oxygen reference wafers (supplied by Siltec Silicon) and samples analyzed for total oxygen by SIMS (analysis by Charles Evans and Associates) are included in this study.

O_i Analysis Techniques

The software package developed for this study is able to analyze FTIR absorbance or transmittance data and calculate O_i according to three separate algorithms: standard test method (STM), short baseline technique (SBT), and curved baseline technique (CBT). STM is based on ASTM F1188.²⁰ While STM is perhaps the most straightforward of the three algorithms and is reported to work well with lightly doped silicon, it inadequately compensates for the baseline curvature inherent in FTIR spectra from heavily doped silicon. SBT, which reduces curvature effects in the IR measurements for single-side polished wafers, was reported by Series and Griffiths.¹⁸ Oates and Lin extended this line of research to heavily doped n-type and p-type silicon by thinning and double-side polishing.⁸ SBT reduces the error due to curvature effects related to free carrier absorption; however, a careful calibration is required to fully exploit this method. Very recently, CBT, with a simpler analytical calibration, was reported to give results equivalent to the short baseline technique.⁹ In the subsections that follow, we describe the basic algorithms for STM, SBT, and CBT.

Standard Test Method (STM)

First, we obtain an FTIR transmittance or absorbance spectrum over the range 900 to 1300 cm⁻¹. Figures 4a and 4b show typical transmittance and absorbance spectra, respectively. Calculations in STM are performed in transmittance units, where unity represents 100% transmittance. Percent transmittance must be converted to decimal transmittance (i.e. 50% transmittance must be converted to .50 transmittance units). Decimal absorbance (A) must also be converted to decimal transmittance (T) using the relationship $T = 10^{-A}$.

The O_i calculation is based on net absorption coefficient, where net absorption coefficient is defined as the difference between peak absorption coefficient and baseline absorption coefficient. To calculate peak absorption coefficient and baseline absorption coefficient, we must obtain peak transmittance and baseline transmittance, respectively.

The peak transmittance (T_{peak}) is defined as the minimum transmittance in the wavenumber range 1102 to 1112 cm⁻¹. The wavenumber at which T_{peak} occurs can be referred to as W_{peak}. We construct a baseline using the average transmittance in the regions from 900 to 1000 cm⁻¹, and 1200 to 1300 cm⁻¹ to define the endpoints of a straight line. The baseline transmittance (T_{base}) is then defined as the transmittance value along the baseline that occurs at W_{peak}. Figure 5 illustrates the concept. For our implementation of this algorithm, the user is not constrained to the six wavenumbers mentioned above. The software provides queries for the bounds of choice, allowing the user to accept all, some, or none of the default values. The capability to enter preferred wavenumbers allows the user wide latitude in establishing the peak and baseline. As shown in Table 1, we exercised this option and selected wavenumber region 960 to 1040 cm⁻¹ instead of the default range of 900 to 1000 cm⁻¹ to form one end of the baseline.

Absorption coefficients (AC) are calculated from transmittance, accounting for multiple reflection, with the relationship:

$$AC = -x^{-1} \ln [(L^4 + M)^{0.5} - L^2] + N] \quad (1)$$

where: x = sample thickness (cm)
 $L = 1 - R$
 $M = 4R^2T^2$
 $N = 2R^2T$
 R = reflectivity (0.30 for lightly P-doped, 0.29 for heavily Sb-doped)
 T = transmittance

Equation 1, although mathematically correct, was discovered to be numerically unstable over certain data sets. Precision was being lost (i.e. round-off error was being introduced) when subtracting similarly small numbers in the numerator of the $\ln$ argument (i.e. $(L^4 + M)^{0.5}$ closely approximates L^2). To minimize numerical instability and to preserve information that might otherwise be lost, Equation 1 was algebraically reworked (through conjugate multiplication) to produce:

$$AC = -x^{-1} \ln [2T + ((L^4 + M)^{0.5} + L^2)] \quad (2)$$

Notice that the subtraction operation has been converted to an addition operation by this simple algebraic trick. Small intermediate values are now summed instead of subtracted, reducing the likelihood of lost information.

The peak absorption coefficient (AC_{peak}) is calculated by substituting T_{peak} for T in Equation 2. Similarly, the baseline absorption coefficient (AC_{base}) is calculated by substituting T_{base} for T in Equation 2. The net absorption coefficient (AC_{net}) is simply $AC_{peak} - AC_{base}$ - phonon contribution. The accepted value of the phonon contribution is 0.5. The O_i content of the silicon sample is obtained by multiplying AC_{net} by a known calibration factor such as OLD ASTM, DIN/NEW ASTM, IOC-88, or JEIDA. The results are reported in ppm or atoms/cm³. A thorough discussion of FTIR calibration methods and correction factors is presented in recent publications.^{24,25}

Equations 1 and 2 are correct when the spectra are obtained with single beam FTIR spectrometers with normal incidence. ASTM F1188 was reworked in 1993 to include data from double beam dispersive instruments. The procedure for calculating O_i is the same for the revised formula. Table 1 provides an example of the software output for STM using the 1988 version of F1188. All STM O_i data in this report are calculated using the 1988 version of F1188.

There exists a partial diagnostic for the validity of O_i values obtained by STM. The full width at half maximum (FWHM) of the oxygen-in-silicon band at a temperature of 300 K is 32 cm⁻¹. O_i calculations from spectral data having a FWHM greater than 32 cm⁻¹ will be in error. The software computes and reports the FWHM of all spectral data.

The precision of the STM depends on the thickness, resistivity, and oxygen content of the test specimen. The inherent limitations in thickness and resistivity (the free carrier absorption effect discussed earlier) are important parameters we sought to characterize. We will discuss these limitations later in the results and discussion section of this paper.

The useful range of oxygen concentrations measurable by the method is from 10^{16} atoms/cm³ to the maximum amount of O_i soluble in silicon. The single instrument repeatability of ASTM F1188 was studied in a recent experiment in which the oxygen content of equivalent samples (O_i ranging from 5 to 30 ppma) were measured by different laboratories.²⁵ The single instrument repeatability of the method, pooled over all specimens in the test set, ranged from 0.4 to 1.2%. The multilaboratory reproducibility was determined in the same study to be $\pm 3\%$.

Short Baseline Technique (SBT)

SBT uses spectral data in the range 1080 to 1130 cm⁻¹ in an integrated area approach rather than the peak height approach used by STM. However, since the only existing conversion factors for O_i relate the peak height to the oxygen concentration, SBT requires calibration coefficients because it does not measure the peak height of the 1106 cm⁻¹ band. These calibration coefficients are determined from float-zone (FZ) and Czochralski (CZ) standards prior to the analysis of unknown test specimens. SBT is divided into two parts: calibration and oxygen analysis.

Part I. Calibration

The calibration process uses 2 mm thick, double-side polished, high resistivity (greater than 5 Ω -cm) FZ and CZ wafers. The calibration process is also divided into two procedures: determination of net absorption coefficient of CZ standard, and calculation of FZ and CZ calibration coefficients.

Procedure 1: Determination of net absorption coefficient of CZ standard

First, we obtain a CZ FTIR transmittance or absorbance spectrum over the range 900 to 1300 cm⁻¹. As noted previously, Figures 4a and 4b show typical transmittance and absorbance spectra, respectively. Calculations in SBT are performed in absorbance units, where unity represents 100% absorbance. Percent absorbance must be converted to decimal absorbance (i.e. 50% absorbance must be converted to .50 absorbance units). Decimal transmittance (T) must also be converted to decimal absorbance (A) using the relationship $A = -\log_{10}T$.

Determine A₁, A₂, and A₃ by calculating the mean of the absorbance data points in the three regions below:

A₁: 1037 to 1040 cm⁻¹ (inclusive)

A₂: 1232 to 1241 cm⁻¹ (inclusive)

A₃: 1103 to 1111 cm⁻¹ (inclusive)

For our implementation of this algorithm, the user is not constrained to the six wavenumbers mentioned above. The software provides queries for the bounds of choice, allowing the user to accept all, some, or none of the default values. The capability to enter preferred wavenumbers allows the user wide latitude in establishing A₁, A₂, and A₃.

Corrected absorbances (CA) are calculated from absorbance, accounting for multiple reflection, with the relationship:

$$CA = -\ln [2K + ((L^4 + M)^{0.5} + L^2)] \quad (3)$$

where: $K = T = 10^{-A}$

$L = 1 - R$

$M = 4R^2K^2$

R = reflectivity (0.30 for lightly P-doped)

A = absorbance

Equation 3 is nearly identical in form to Equation 2. Equation 3 substitutes 10^{-A} in place of T , so that the calculations can be performed in absorbance units. Secondly, since corrected absorbances should remain independent of sample thickness at this juncture, we omit the sample thickness term, x , in Equation 3. The sample thickness will be reintroduced in Equation 5.

Now, we individually substitute A_1 , A_2 , and A_3 for A in Equation 3 to obtain CA_1 , CA_2 , and CA_3 , respectively. We determine the baseline subtracted area under the absorption band with the relationship:

$$\text{area} = CA_3 - ((CA_2(E_1) + CA_1(E_2)) + E_3) \quad (4)$$

where: $E_1 = ((1241 \text{ cm}^{-1} - 1111 \text{ cm}^{-1}) + (1232 \text{ cm}^{-1} - 1103 \text{ cm}^{-1})) + 2 \text{ cm}^{-1}$

$E_2 = ((1111 \text{ cm}^{-1} - 1040 \text{ cm}^{-1}) + (1103 \text{ cm}^{-1} - 1037 \text{ cm}^{-1})) + 2 \text{ cm}^{-1}$

$E_3 = ((1241 \text{ cm}^{-1} - 1040 \text{ cm}^{-1}) + (1232 \text{ cm}^{-1} - 1037 \text{ cm}^{-1})) + 2 \text{ cm}^{-1}$

The net absorption coefficient (AC_{net}) is obtained with the equation:

$$AC_{\text{net}} = (\text{area} + x) - y \quad (5)$$

where: x = thickness of CZ wafer (cm)

y = phonon contribution (0.5)

AC_{net} is passed to Procedure 2 for use in calculating the CZ calibration coefficients. Although the actual O_i content of the CZ standard is not needed in Procedure 2, the value is calculated and displayed as an aid to the user. The O_i content of the CZ standard can be obtained by multiplying AC_{net} by a known calibration factor such as OLD ASTM, DIN/NEW ASTM, IOC-88, or JEIDA. The results are reported in ppm or atoms/cm³. A thorough discussion of FTIR calibration methods and correction factors are presented in recent publications.^{24,25}

We next calculate the six calibration coefficients K_i^{FZ} and K_i^{CZ} ($i = 1, 2, 3$) which correspond to the silicon and oxygen absorptivities, respectively, in each of the three regions of the 1106 cm^{-1} band used in this procedure.

Procedure 2: Calculation of FZ and CZ calibration coefficients

First, we obtain both FZ and CZ FTIR transmittance or absorbance spectra over the range 1080 to 1130 cm^{-1} . If desired, the CZ spectra obtained in Procedure 1 can be utilized to satisfy the CZ requirement in Procedure 2. Calculations in SBT are performed in absorbance units, where unity represents 100% absorbance. Percent absorbance must be converted to decimal absorbance (i.e. 50% absorbance must be converted to .50 absorbance units). Decimal transmittance (T) must also be converted to decimal absorbance (A) using the relationship $A = -\log T$.

For each spectrum, we determine A₁, A₂, A₃, A₄, and A₅ by calculating the mean of the absorbance data points in the five regions below:

A₁: 1080 to 1089 cm^{-1} (inclusive)

A₂: 1090 to 1099 cm^{-1} (inclusive)

A₃: 1100 to 1109 cm^{-1} (inclusive)

A₄: 1110 to 1119 cm^{-1} (inclusive)

A₅: 1120 to 1129 cm^{-1} (inclusive)

For each spectrum, we correct A₁, A₂, A₃, A₄, and A₅ for multiple reflection using Equation 3 (i.e. substitute A₁, A₂, A₃, A₄, and A₅ for A in Equation 3 to obtain CA₁, CA₂, CA₃, CA₄, and CA₅, respectively).

For each spectrum, we adjust CA₂, CA₃, and CA₄ for a linear baseline fitted through CA₁ and CA₅ to give B₂, B₃, and B₄:

$$B_2 = CA_2 - 0.25(CA_5) - 0.75(CA_1) \quad (6)$$

$$B_3 = CA_3 - 0.50(CA_5) - 0.50(CA_1) \quad (7)$$

$$B_4 = CA_4 - 0.75(CA_5) - 0.25(CA_1) \quad (8)$$

The six calibration coefficients K_i^{FZ} and K_i^{CZ} ($i = 1, 2, 3$) are calculated using:

$$K_1^{\text{FZ}} = B_4^{\text{FZ}} + x^{\text{FZ}} \quad (9)$$

$$K_2^{\text{FZ}} = B_3^{\text{FZ}} + x^{\text{FZ}} \quad (10)$$

$$K_3^{\text{FZ}} = B_2^{\text{FZ}} + x^{\text{FZ}} \quad (11)$$

$$K_1^{\text{CZ}} = (B_4^{\text{CZ}} - x^{\text{CZ}}K_1^{\text{FZ}}) + (x^{\text{CZ}}AC_{\text{net}}) \quad (12)$$

$$K_2^{\text{CZ}} = (B_3^{\text{CZ}} - x^{\text{CZ}}K_2^{\text{FZ}}) + (x^{\text{CZ}}AC_{\text{net}}) \quad (13)$$

$$K_3^{\text{CZ}} = (B_2^{\text{CZ}} - x^{\text{CZ}}K_3^{\text{FZ}}) + (x^{\text{CZ}}AC_{\text{net}}) \quad (14)$$

where: x^{FZ} = thickness of FZ wafer (cm)

x^{CZ} = thickness of CZ wafer (cm)

AC_{net} = net absorption coefficient of CZ std (result from Procedure 1)

Using the coefficients gathered from the calibration process, we now proceed to compute the O_i content of the unknown samples.

Part II. Oxygen Analysis

First, we obtain a sample FTIR transmittance or absorbance spectra over the range 1080 to 1130 cm^{-1} . Calculations in the SBT are performed in absorbance units, where unity represents 100% absorbance. Percent absorbance must be converted to decimal absorbance (i.e. 50% absorbance must be converted to .50 absorbance units). Decimal transmittance (T) must also be converted to decimal absorbance (A) using the relationship $A = -\log T$.

We determine A_1 , A_2 , A_3 , A_4 , and A_5 by calculating the mean of the absorbance data points in the five regions below:

A_1 : 1080 to 1089 cm^{-1} (inclusive)

A_2 : 1090 to 1099 cm^{-1} (inclusive)

A_3 : 1100 to 1109 cm^{-1} (inclusive)

A_4 : 1110 to 1119 cm^{-1} (inclusive)

A_5 : 1120 to 1129 cm^{-1} (inclusive)

We correct A_1 , A_2 , A_3 , A_4 , and A_5 for multiple reflection using Equation 3 (i.e. substitute A_1 , A_2 , A_3 , A_4 , and A_5 for A in Equation 3 to obtain CA_1 , CA_2 , CA_3 , CA_4 , and CA_5 , respectively).

We adjust CA_2 , CA_3 , and CA_4 for a linear baseline fitted through CA_1 and CA_5 using Equations 6, 7, and 8 to give B_2 , B_3 , and B_4 .

We calculate $AC_{\text{net}1}$, $AC_{\text{net}2}$, and $AC_{\text{net}3}$ (the three estimates of the net absorption coefficient) from B_2 , B_3 , B_4 , and the six calibration coefficients determined in Part I:

$$AC_{\text{net}1} = (B_4 - xK_1^{\text{FZ}}) + (xK_1^{\text{CZ}}) \quad (15)$$

$$AC_{\text{net}2} = (B_3 - xK_2^{\text{FZ}}) + (xK_2^{\text{CZ}}) \quad (16)$$

$$AC_{\text{net}3} = (B_2 - xK_3^{\text{FZ}}) + (xK_3^{\text{CZ}}) \quad (17)$$

where: x = thickness of sample wafer (cm)

Finally, we calculate the average of the net absorption coefficients:

$$AC_{\text{avg}} = (AC_{\text{net}1} + AC_{\text{net}2} + AC_{\text{net}3}) / 3 \quad (18)$$

The O_i content of the silicon sample is obtained by multiplying AC_{avg} by a known calibration factor such as OLD ASTM, DIN/NEW ASTM, IOC-88, or JEIDA. The results are reported in ppm or atoms/ cm^3 . A thorough discussion of FTIR calibration methods and correction factors is presented in recent publications.^{24,25} Table 2 provides an example of the software output for SBT.

SBT has several algorithmic advantages over STM when the substrate is heavily doped. While STM uses the entire spectral range of 900 to 1300 cm^{-1} to establish the baseline and calculate the peak height, SBT uses the much shorter spectral range 1080 to 1130 cm^{-1} in an integrated area approach. Figure 6 contrasts the baseline constructions of STM and SBT. The short baseline algorithm has the desired effect of minimizing the effect of curvature on the oxygen analysis. As discussed earlier, the frequency dependence of the free carrier absorption in heavily doped silicon causes significant baseline curvature and shrouds the weak O_i band. A second algorithmic advantage of SBT concerns noise detection. Since three estimates of O_i are obtained from each sample, noise degradation of the spectra can be evaluated through a simple comparison of the three values. We will present a more detailed description of these advantages later in the results and discussion section.

Curved Baseline Technique (CBT)

CBT uses spectral data in the range 1000 to 1300 cm^{-1} in a modified peak height approach similar to STM. As discussed in the previous section, since the only existing conversion factors for O_i relate the peak height to the oxygen concentration, SBT requires calibration coefficients because it does not measure the peak height of the 1106 cm^{-1} band. These calibration coefficients are determined from FZ and CZ standards prior to the analysis of unknown test specimens. This careful calibration procedure has, on occasion, been unwieldy and time consuming. It also requires the user to possess quality FZ and CZ standards which may not be readily available. CBT has been developed to alleviate the need for such careful and potentially problematic calibration procedures.

The O_i calculation is based on net absorption coefficient, where net absorption coefficient is defined as the difference between peak absorption coefficient and baseline absorption coefficient. In STM, we obtained peak transmittance and baseline transmittance to calculate peak absorption coefficient and baseline absorption coefficient, respectively. That algorithm forces the construction of a purely linear baseline. While a linear baseline correctly models the spectral behavior we observe with lightly doped silicon, it does not adequately describe the shape of the spectra we observe with heavily doped silicon. Therefore, in CBT, we wish to develop a polynomial-fitted relationship which models more accurately the curved baseline associated with free carrier absorption effects.

Borghesi, et. al. suggest a model which we have adopted as the basis for our curved baseline technique.⁹ They suggest a Drude-like complex dielectric function for the fit. It is well known that this complex dielectric function is valid for nondegenerate semiconductors.^{26,27} This function has also been used to analyze semiconductors that are heavily doped.^{28,29,30} From this function we obtain the desired expression for absorption coefficient:

$$\alpha = K\lambda^2 + c \quad (19)$$

where: α = absorption coefficient
 λ = wavelength
 K and c are constants

First, we obtain an FTIR transmittance or absorbance spectrum over the range 1000 to 1300 cm^{-1} . Calculations in CBT are performed in transmittance units, where unity represents 100% transmittance. Percent transmittance must be converted to decimal transmittance (i.e. 50% transmittance must be converted to .50 transmittance units). Decimal absorbance (A) must also be converted to decimal transmittance (T) using the relationship $T = 10^{-A}$.

As shown in Figure 7b, we create an absorption coefficient vs. wavelength² domain from the original transmittance vs. wavenumber data (Figure 7a). Wavenumbers are transformed to wavelengths² using the reciprocal relationship that exists between the two entities. Transmittances are transformed to absorption coefficients using Equation 2.

The peak absorption coefficient (AC_{peak}) is defined as the average absorption coefficient in the wavenumber range 1103 to 1111 cm^{-1} . The wavenumber at which AC_{peak} occurs can be referred to as W_{peak} . Figure 8 illustrates the concept. To solve for the baseline absorption coefficient (AC_{base}), while correcting for the background absorption due to the free carrier absorption, we fit the baseline data to the 2nd order polynomial shown in Equation 19 using a least-squares fitting algorithm. We use the two wavenumber regions from 1000 to 1040 cm^{-1} and 1220 to 1300 cm^{-1} to form the ends of the baseline that is to be constructed. The central region from 1040 to 1220 cm^{-1} is excluded because it contains the oxygen and phonon structures that are most subject to curvature effects caused by free carrier absorption. AC_{base} is defined as the absorption coefficient along the baseline that occurs at W_{peak} . Figures 9a and 9b illustrate the concept.

In our implementation of the algorithm, the user is not restricted to the six wavenumbers mentioned above. The software provides queries for the bounds, allowing the user to accept all, some, or none of the default values. The capability to enter wavenumbers allows the user wide latitude in establishing the peak and baseline. As shown in Figure 9, we exercised this option and selected wavenumber region 1210 to 1250 cm^{-1} instead of the default range of 1220 to 1300 cm^{-1} to form one end of the baseline.

The net absorption coefficient (AC_{net}) is $AC_{\text{peak}} - AC_{\text{base}} - \text{phonon contribution}$. The accepted value of the phonon contribution is 0.5. The O_i content of the silicon sample is obtained by multiplying AC_{net} by a known calibration factor such as OLD ASTM, DIN/NEW ASTM, IOC-88, or JEIDA. The results are reported in ppm or atoms/ cm^3 . A thorough discussion of FTIR calibration methods and correction factors is presented in recent publications.^{24,25} Table 3 provides an example of the software output for CBT.

Although vastly different, the curved baseline algorithm and the short baseline algorithm both have the desired effect of minimizing the effect of curvature on the oxygen analysis. As discussed earlier, the frequency dependence of the free carrier absorption in heavily doped silicon causes significant baseline curvature and shrouds the weak O_i band. SBT maintains the advantage in noise detection since noise degradation of the spectra can be evaluated through a simple comparison of the three estimates of O_i . Since CBT calculates only one estimate of O_i , it cannot provide simple insight into noise degradation. CBT, however, eliminates the tedious and somewhat unwieldy calibration requirements of SBT, thereby exhibiting an important practical advantage over SBT in ease and convenience. Figure 10 contrasts the baseline constructions of STM, SBT, and CBT. We present a more detailed discussion of these advantages in the next section.

Results and Discussion

We sought first to characterize the experimental/instrumental error that clouds the comparisons of the three O_i analytical techniques. Since our ultimate goal was to discover which technique was most applicable to heavily doped substrates, we did not wish to attribute differences in O_i results among the three techniques to the "correctness" of a particular technique if the differences were due to variations in experimental procedure or instrument reproducibility. In clarification of "correctness", we do not infer that one technique is more correct than another in any absolute sense, but rather that each technique has operational limits and that beyond those limits, they tend to deviate.

We began, therefore, by investigating the reproducibility of O_i measurements on well-resolved peaks (i. e. lightly doped silicon). We next investigated the reproducibility on poorly resolved peaks (i. e. heavily doped silicon). After addressing the reproducibility issue, we contrasted the performance of the three O_i analytical techniques using only lightly doped substrates. Last, we contrasted the results of the three O_i analytical techniques using only heavily doped substrates.

Reproducibility With Well-Resolved Peaks

Well-resolved peaks (nominal resistivities greater than $\sim 0.03 \Omega\text{-cm}$) are the natural result of lightly doped wafers (i. e. the absence of free carrier absorption effects). Table 4 provides the results of an investigation of reproducibility with well-resolved peaks. A single thinned n-type wafer of $252 \mu\text{m}$ thickness and $0.0304 \Omega\text{-cm}$ resistivity was measured six different times over a period of four weeks on a single FTIR spectrometer (Nicolet 60SX) and analyzed each time using STM, SBT, and CBT. All O_i calculations are based on the IOC-88 calibration factor of 6.28.

We note that this wafer is on the border between lightly doped and heavily doped for the purposes of free carrier absorption. It would certainly be possible to obtain better peak resolution by testing a wafer of higher resistivity, but we wish to investigate this borderline region because it defines the best reproducibility we are likely to obtain with heavily doped wafers. By generating six discrete FTIR spectra from a single substrate, we were able to inspect the range of O_i values that were produced by each technique and thereby formulate opinions about experimental/instrumental variations.

As Table 4 illustrates, standard deviations (i. e. σ) of 0.4 ppm, 0.4 ppm, and 0.5 ppm were produced by STM, SBT, and CBT, respectively. The reproducibility is, therefore, quite similar for each of the three techniques, with no trend toward tighter distributions as you move from STM to SBT to CBT. As Table 4 also illustrates, the three techniques produce statistically identical O_i results. The O_i ranges of 18.8 to 19.8 ppm, 18.5 to 19.6 ppm, and 17.7 to 18.8 ppm, for STM, SBT, and CBT, respectively, demonstrate clear overlap. The average O_i values of 19.3 ppm, 19.0 ppm, and 18.4 ppm appear relatively steady within statistical certainty (i. e. $2\sigma = \sim 1 \text{ ppm}$). It is worth noting, however, that CBT consistently produced results that were less than those of SBT. STM results were also generally higher than SBT and CBT results, suggesting a slightly decreasing trend from STM to SBT to CBT.

The SIMS value of 19.9 ppm provides a reference value for comparison and "correctness" evaluation of STM, SBT, and CBT. To facilitate straightforward comparisons between SIMS results and FTIR results, we decided earlier to operate under the belief that essentially all of the oxygen is in interstitial form, although we cannot totally discount the possibility that SIMS may provide us with an overestimation of O_i , since the SIMS result is actually total oxygen content ($O_i + O_p$).

Although SIMS and FTIR results should agree within the experimental error of each method under our belief that essentially all of the oxygen is in interstitial form, we observe a small statistical variation between the SIMS and FTIR values. The SIMS value is slightly greater than each of the STM, SBT, and CBT values. While it is conceivable that all three techniques have underestimated the true O_i , it is more likely that they are "correct" owing to the independent nature of their calculations and the observed tight distribution of O_i values that result from these calculations. We are left to consider the possibility that the FTIR spectral data are somehow slightly awry, or perhaps the SIMS estimate is indeed a slight overestimation in this case. Irrespective of the correct explanation, the statistical variation between SIMS and FTIR results is quite small and the true purpose of this comparison was to highlight differences between STM, SBT, and CBT values, with respect to SIMS values. We are, therefore, satisfied that the true O_i content of the subject wafer is bounded above by a value of 19.9 ± 0.1 ppm and that STM, SBT, and CBT are equally reproducible with well-resolved peaks.

The statistical variation between the FTIR results and the SIMS benchmark, although quite small, leaves us unable to comment on the "correctness" of each of the three techniques, nor do the data fully support an attempt to rank the three techniques in terms of level of "correctness". In the section "Results on Lightly Doped Silicon", we enlarge the data set to seven different wafers of significantly higher resistivities in an attempt to discover a hierarchy of "correctness" in lightly doped substrates if, indeed, such a hierarchy exists.

Based upon these observations, we would not expect disparate O_i results between the three techniques (i. e. results that differ by more than ± 1 ppm nominally on $\sim 0.03 \Omega\text{-cm}$ or higher substrates) to be a consequence of experimental procedure or instrumental variability, but rather a true predictor of the "correctness" of each technique. We might even expect O_i differences amongst the three techniques of less than ± 1 ppm to be statistically significant for wafers that are more lightly doped than our test wafer (i. e. resistivities higher than $0.0304 \Omega\text{-cm}$).

Reproducibility With Poorly-Resolved Peaks

Poorly-resolved peaks (nominal resistivities less than $\sim 0.03 \Omega\text{-cm}$) are the natural result of free carrier absorption effects in heavily doped wafers. Table 5 provides the results of an investigation of reproducibility with poorly-resolved peaks. A single thinned n-type wafer of $161 \mu\text{m}$ thickness and $0.0138 \Omega\text{-cm}$ resistivity was measured six different times over a period of four weeks on a single FTIR spectrometer (Nicolet 60SX) and analyzed each time using STM, SBT, and CBT. All O_i calculations are based on the IOC-88 calibration factor of 6.28.

It would certainly be possible to obtain better peak resolution by testing a wafer of higher resistivity (closer to $0.03 \Omega\text{-cm}$), but we wish to investigate this low resistivity region because it defines the worst reproducibility we are likely to obtain with heavily doped

wafers. By generating six discrete FTIR spectra from a single substrate, we were able to inspect the range of O_i values that were produced by each technique and thereby formulate opinions about experimental/instrumental variations.

As Table 5 illustrates, standard deviations (i. e. σ) of 1.8 ppm, 1.0 ppm, and 0.7 ppm were produced by STM, SBT, and CBT, respectively. The reproducibility is quite similar for SBT and CBT, although the trend is toward tighter data distributions as you move from STM to SBT to CBT. The standard deviation of the STM data is significantly higher than SBT and CBT standard deviations. STM does not appear to be as reproducible with heavily doped material. As Table 5 also illustrates, STM calculations exhibit the largest absolute O_i values (21.6 to 26.3 ppm). The O_i ranges of 16.0 to 18.3 ppm and 14.9 to 16.9 ppm for SBT and CBT, respectively, demonstrate clear overlap. The average O_i value of 23.4 ppm for STM appears quite disparate with the 17.1 ppm and 16.2 ppm average values from SBT and CBT, respectively. The average values from SBT and CBT, however, appear relatively steady within statistical certainty (i. e. $2\sigma = \sim 2$ ppm). SBT and CBT produce statistically identical O_i results. It is worth noting, however, that CBT consistently produced results that were less than those of SBT.

The SIMS value of 17.7 ppm provides a reference value for comparison and "correctness" evaluation of STM, SBT, and CBT. To facilitate straightforward comparisons between SIMS results and FTIR results, we decided earlier to operate under the belief that essentially all of the oxygen is in interstitial form, although we cannot totally discount the possibility that SIMS may provide us with an overestimation of O_i , since the SIMS result is actually total oxygen content ($O_i + O_p$).

Although SIMS and FTIR results should agree within the experimental error of each method under our belief that essentially all of the oxygen is in interstitial form, we observe statistical variations between the SIMS and FTIR values. The SIMS value of 17.7 ± 0.2 is significantly smaller than the STM value of 23.4 ± 1.8 and slightly greater than the CBT value of 16.2 ± 0.7 . SIMS and SBT agree within the experimental error of each method. The rather large discrepancy between STM and the SIMS benchmark leads us to conclude that the STM results of 21.6 to 26.3 are not "correct". As with well-resolved peaks, we are unable to assert the "correctness" of the CBT results since they lie just outside the statistical window. Perhaps the SIMS estimate is indeed a slight overestimation in this case as well. Since the statistical variation between SIMS and CBT results is quite small and the true purpose of this comparison was to highlight differences between STM, SBT, and CBT values, with respect to SIMS values, we are, therefore, satisfied that the true O_i content is bounded above by a value of 17.7 ± 0.2 ppm and that SBT and CBT are equally reproducible with poorly-resolved peaks.

The statistical variation between the CBT results and the SIMS benchmark, although quite small, leaves us unable to comment on the "correctness" of the CBT technique, nor do the data fully support an attempt to rank SBT and CBT in terms of level of "correctness". In the section "Results on Heavily Doped Silicon", we enlarge the data set to seven different heavily doped wafers in an attempt to discover which of the two techniques is more "correct" in heavily doped substrates if, indeed, such a hierarchy exists.

Based upon these observations, we would not expect disparate O_i results between SBT and CBT (i. e. results that differ by more than ± 2 ppm nominally on $0.0138 \Omega\text{-cm}$ to $\sim 0.03 \Omega\text{-cm}$ substrates) to be a consequence of experimental procedure or instrumental variability, but rather a true predictor of the "correctness" of each technique.

Results on Lightly Doped Silicon

Table 6 contrasts the performance of the three O_i analytical techniques using only lightly doped substrates. Seven different lightly doped (2.26 to 100 Ω -cm resistivity) silicon samples were measured on a single FTIR spectrometer (Nicolet 60SX) and analyzed using STM, SBT, and CBT. All O_i calculations are based on the IOC-88 calibration factor of 6.28. The seven wafers are similar, but not identical, in thickness (438 to 598 μ m). A SIMS analysis was also performed on each of the seven wafers.

Inspection of the table shows similar results from STM, SBT, and CBT. Almost without exception, the O_i values from each sample remain steady within statistical certainty (i. e. $2\sigma = \sim 1$ ppm). An exception to this steadiness is apparent in wafer "FZ1". Results from wafer "FZ1" show a difference of 1.5 ppm between the high and low O_i values. In the reproducibility study on well-resolved peaks it was discovered that disparate results between techniques (i. e. results that differ by more than ± 1 ppm nominally on ~ 0.03 Ω -cm or higher substrates) were not a consequence of experimental procedure or instrumental variability, but rather a true predictor of the "correctness" of each technique. A possible explanation for the behavior of "FZ1" is discussed later in this section.

It is also worth noting that the slightly decreasing trend in O_i values that we observed from STM to SBT to CBT in the reproducibility study with well-resolved peaks (Table 4) is not observed in the results of lightly doped silicon (Table 6). In fact, CBT no longer consistently produces results that are less than those of SBT, nor does STM produce results that are generally higher than SBT and CBT results. Substrate resistivity provides the necessary explanation (i. e. the resistivities in Table 6 are ~ 2 orders-of-magnitude larger than the resistivity in Table 4). Little or no free carrier absorption occurs in silicon of such high resistivity. As substrate resistivity increases, the three techniques converge, producing similar O_i results.

Although SIMS and FTIR results should agree within the experimental error of each method under our belief that essentially all of the oxygen is in interstitial form, we again observe small statistical variations between the SIMS and FTIR values. Wafers "14242", "34222", "LOO2", and "FZ1" (discounting the outlying CBT result) display full statistical agreement between STM, SBT, CBT, and SIMS values. The CBT value on wafer "FZ1" may be viewed with some suspicion as the value of 2.2 ppm calculated by CBT significantly exceeds the values of 0.8 ppm and 0.7 ppm calculated by STM and SBT, respectively. The 2.2 ppm CBT value is also twofold greater than the SIMS estimate. The CBT value is, therefore, unlikely to be the "correct" answer. Some unknown error may be present or perhaps CBT begins to break down at low O_i levels or high substrate resistivities. Wafer "FZ1" has the highest resistivity of any of the substrates at > 100 Ω -cm.

For the remaining three wafers, "13232", "05222", and "DSP1", the O_i values calculated by STM, SBT, and CBT show a pattern of being consistently below the respective SIMS values. We are left to consider the possibility that the FTIR spectral data are somehow slightly awry, or perhaps the SIMS estimates are indeed slight overestimations in some instances. Irrespective of the correct explanation, the statistical variation between SIMS and FTIR results is quite small and the true purpose of this comparison was to highlight differences between STM, SBT, and CBT values, with respect to SIMS values.

The statistical variations between the FTIR results and the SIMS benchmarks, although generally quite small, leaves us unable to comment on the "correctness" of the three techniques, nor do the data, as in the reproducibility study of well-resolved peaks (Table 4), fully support an attempt to rank the three techniques in terms of level of "correctness".

Results on Heavily Doped Silicon

Table 7 contrasts the performance of the three O_i analytical techniques using only heavily doped substrates. Seven different heavily doped (.0089 to .0304 Ω -cm resistivity) silicon samples were measured on a single FTIR spectrometer (Nicolet 60SX) and analyzed using STM, SBT, and CBT. All O_i calculations are based on the IOC-88 calibration factor of 6.28. The seven wafers are similar in thickness (125 to 390 μ m). All wafers except "DSP2" were SE thinned. Wafer "DSP2" was mechanically thinned and double-side polished. A SIMS analysis was also performed on each of the seven wafers. As a final note, wafers "14321", "HO21", and "MO21" received some thermal processing which may have led to slightly lower O_i values than existed initially.

Inspection of the table shows similar results from SBT and CBT. Without exception, the O_i values from each sample remain steady within statistical certainty. STM, however, produces O_i values that are outside the statistical window with SBT and CBT (excluding wafers "3043" where the statistical criteria is satisfied for reasons explained below and "14321" which just falls within the statistical window). In the reproducibility study on poorly-resolved peaks it was discovered that disparate results between techniques (i. e. results that differ by more than ± 2 ppm nominally on 0.0138 Ω -cm to ~ 0.03 Ω -cm substrates) were not a consequence of experimental procedure or instrumental variability, but rather a true predictor of the "correctness" of each technique. STM values are, therefore, not consistently "correct" for this group of heavily doped material since they exceed SBT and CBT values by 1.5 to 7.2 ppm.

This result agrees with previous evidence that STM does not produce consistent results for heavily doped silicon because of high free carrier absorption.³¹ Additional work supports the divergence of STM with substrate resistivities below 0.1 Ω -cm.²⁰ Using special wafer preparations, however, researchers have been able to use STM on heavily doped substrates with some success.³¹ It is also worth noting in Table 7 that CBT consistently produced results that were less than those of SBT.

It should be noted that results from wafer "3043" (0.0304 Ω -cm resistivity and hence, on the border between lightly doped and heavily doped) are an average of data from Table 4 (reproducibility with well-resolved peaks) and have been included in Table 7 to demonstrate that the three techniques converge to similar results as the resistivity increases. This borderline region provides the best agreement between the three techniques that we are likely to obtain with heavily doped wafers.

It should also be noted that results from wafer "SB4" (0.0138 Ω -cm resistivity) are an average of data from Table 5 (reproducibility with poorly-resolved peaks) and have been included in Table 7 for completeness. From our group of seven heavily doped wafers (.0089 to .0304 Ω -cm resistivity), STM produces five "incorrect" results. While not conclusive proof of the inappropriateness of STM on heavily doped silicon, this finding provides a convincing argument that STM is not a reliable way to calculate O_i in heavily doped material.

Although SIMS and FTIR results should agree within the experimental error of each method under our belief that essentially all of the oxygen is in interstitial form, we again observe statistical variations between the SIMS and FTIR values. In general, the SIMS values are significantly smaller than the STM values and slightly greater than the CBT values. SIMS and SBT generally agree within the experimental error of each method (with the possible exception of wafers "HO21" and "3043").

The rather large discrepancy between STM values and SIMS benchmarks leads us to conclude that the STM results are not "correct". The O_i values returned by STM generally exceed the respective SIMS values by a significant amount (with the possible exception of wafers "14321", "HO21", and "3043"). As discussed earlier, either the FTIR spectral data from wafer "3043" is slightly awry or the SIMS result from wafer "3043" is a slight overestimation. As stated earlier, wafers "14321" and "HO21" received some thermal processing which may have led to slightly lower O_i values than existed initially.

As with poorly-resolved peaks, the CBT results lie just outside the statistical window. Perhaps the SIMS estimates are indeed slight overestimations. Irrespective of the correct explanation, the statistical variations between SIMS and CBT results are not large and the true purpose of this comparison was to highlight differences between STM, SBT, and CBT values, with respect to SIMS values. Nevertheless, the statistical variations between the CBT results and the SIMS benchmarks leave us unable to comment on the "correctness" of the CBT technique, nor do the data, as in the reproducibility study of poorly-resolved peaks (Table 5), fully support an attempt to rank the SBT and CBT techniques in terms of level of "correctness". The behavior of the data in Table 7 is, however, in general agreement with the data generated in the reproducibility study of poorly-resolved peaks (Table 5).

Conclusions

The software package developed for this study is able to analyze FTIR absorbance or transmittance data and calculate O_i according to three separate algorithms: standard test method (STM), short baseline technique (SBT), and curved baseline technique (CBT). While STM is perhaps the most straightforward of the three algorithms, it is often unable to adequately compensate for the baseline curvature inherent in many FTIR spectra (i.e. free carrier absorption in heavily doped silicon). SBT reduces the error due to curvature effects related to free carrier absorption; however, a careful calibration is required to fully exploit this method. The recently developed CBT also reduces the error due to curvature effects related to free carrier absorption, but uses a simpler analytical calibration.

The accuracy and reliability of STM depends on the thickness, resistivity, and oxygen content of the test specimen. The inherent limitations in thickness and resistivity are important parameters we sought to characterize. While STM may be confidently used for lightly doped silicon (nominal resistivities greater than $0.03 \Omega\text{-cm}$), it is not an appropriate technique for determining O_i in heavily doped silicon (nominal resistivities less than $0.03 \Omega\text{-cm}$).

SBT has several algorithmic advantages over STM when the substrate is heavily doped. While STM uses the spectral range of 900 to 1300 cm^{-1} to establish the baseline and calculate the peak height, SBT uses the much shorter spectral range 1080 to 1130 cm^{-1} in an integrated area approach. This integrated area approach makes it possible to determine O_i over a wider range of substrate resistivities. Since the only existing conversion factors for O_i relate the peak height to the oxygen concentration, SBT requires calibration coefficients because it does not measure the peak height of the 1106 cm^{-1} band. These calibration coefficients are determined from FZ and CZ standards prior to the analysis of unknown test specimens. This careful calibration procedure has, on occasion, been somewhat unwieldy and time consuming. It also requires the user to possess quality FZ and CZ standards. SBT is an appropriate, although potentially cumbersome, technique for determining O_i in both lightly doped and heavily doped silicon.

CBT uses spectral data in the range 1000 to 1300 cm^{-1} in a modified peak height approach similar to STM. This modified peak height approach makes it possible to determine O_i over a wide range of substrate resistivities. CBT has been developed to alleviate the need for the careful and potentially problematic calibration procedures of SBT. Although different, the curved baseline algorithm and the short baseline algorithm both have the desired effect of minimizing the effect of curvature on the oxygen analysis. As discussed earlier, the frequency dependence of the free carrier absorption in heavily doped silicon causes significant baseline curvature and shrouds the weak O_i band. By eliminating the tedious and somewhat unwieldy calibration requirements of SBT, CBT exhibits an important practical advantage over SBT in ease and convenience of implementation and use. SBT, however, maintains the advantage in noise detection since noise degradation of the spectra can be evaluated through a simple comparison of the three estimates of O_i . Since CBT calculates only one estimate of O_i , it cannot provide simple insight into noise degradation. CBT is an appropriate technique for determining O_i in both lightly doped and heavily doped silicon. For lightly doped wafers, CBT results were very similar to STM and SBT results. For heavily doped wafers, CBT results were systematically lower than SBT results by 1 to 5%.

References

1. R. A. Craven, *Impurity Diffusion and Gettering in Silicon*, Mat. Research Soc. Proc., Vol. 36, p. 159, MRS, Pittsburgh, PA (1985).
2. S. K. Bain, D. P. Griffiths, J. G. Wilkes, R. W. Series, and K. G. Barraclough, *Oxygen Precipitation in Heavily Doped Silicon*, J. Electrochem. Soc., Vol. 137, p. 647 (1990).
3. P. K. Chu, R. S. Hockett, and R. G. Wilson, *Direct Comparison of FTIR and SIMS Calibrations for Oxygen Concentration in Silicon*, Mat. Research Soc. Symp. Proc., Vol. 59, p. 67, Edited by J. W. Corbett, J. C. Mikkelsen, Jr., S. J. Pearton, and S. J. Pennycook, Mat. Research Soc., Pittsburgh, PA (1986).
4. H. He, Y. Li, G. Zhao, R. Yan, Q. Lu, and M. Qi, *Determination of Micro Amounts of Oxygen in Silicon by Inert Gas Fusion*, Talanta, Vol. 30, 10, p. 761 (1983).
5. H. J. Rath, P. Stallhofer, D. Huber, and B. F. Schmitt, *Determination of Oxygen in Silicon by Photon Activation Analysis for Calibration of Infrared Absorption*, J. Electrochem. Soc., Vol. 131, p. 1920 (1984).
6. M. Goldstein and J. Makovsky, *The Calibration and Reproducibility of Oxygen Concentration in Silicon Measurements Using SIMS Characterization Technique*, Semiconductor Fabrication: Technology and Metrology, ASTM STP 990, p. 350, ASTM, Philadelphia, PA (1989).
7. S. Dannefaer and D. Kerr, *Oxygen and Silicon: A Positron Annihilation Investigation*, J. Appl. Phys., Vol. 60, p. 1313 (1986).
8. A. Oates and W. Lin, *Infrared Measurements of Interstitial Oxygen in Heavily Doped Silicon*, J. Crystal Growth, Vol. 89, p. 117 (1988).
9. A. Borghesi, M. Geddo, G. Guizzettiz, and P. Geranzani, *Interstitial Oxygen Determination in Heavily Doped Silicon*, J. Appl. Phys., Vol. 68, p. 1665 (1990).
10. B. Pajot, H. J. Stein, B. Cales, and C. Naud, *Quantitative Spectroscopy of Interstitial Oxygen in Silicon*, J. Electrochem. Soc., Vol. 132, p. 3034 (1985).
11. C. W. Pearce, R. J. Jaccodine, A. J. Filo, and W. Lin, *Oxygen Content of Heavily Doped Silicon*, Appl. Phys. Letters, Vol. 46, p. 887 (1985).
12. ASTM Standards, *Practices for Determination of the Concentration of Impurities in Single Crystal Semiconductor Materials by Infrared Absorption Spectroscopy*, Annual Book of ASTM Standards, ASTM Designation: F 120, ASTM Committee on Standards, Philadelphia, PA.
13. H. J. Hrostowski and R. H. Kaiser, *Infrared Absorption of Oxygen in Silicon*, Phys. Rev., Vol. 107, p. 966 (1957).

14. W. Spitzer and H. Y. Fan, *Infrared Absorption in n-type Silicon*, Phys. Rev., Vol. 108, p. 268 (1957).
15. D. K. Schroder, R. N. Thomas, and J. C. Swartz, *Free Carrier Absorption in Silicon*, IEEE J. Solid State Circuits, Vol. SC 13, p. 180 (1978).
16. W. K. Gladden and A. Baghdadi, *Emerging Semiconductor Technology*, Edited by D. Gupta and P. Langer, ASTM STP 960, p. 353, ASTM, Philadelphia, PA (1987).
17. K. G. Barraclough, R. W. Series, J. S. Hislop, and D. A. Wood, *Calibration of Infrared Absorption by Gamma Activation Analysis for Studies of Oxygen in Silicon*, J. Electrochem. Soc., Vol. 133, p. 187 (1986).
18. R. W. Series and D. P. Griffiths, *Measurement of Oxygen in Device Quality Wafers: United Kingdom Round Robin*, Ext. Abstracts, 169th Meeting Electrochem. Soc., Vol. 86-1, p. 366 (1986).
19. J. W. Medernach, H. J. Stein, and J. O. Stevenson, *Selective Electrochemical Wafer Thinning for Silicon Characterization*, Sandia National Laboratories Report, SAND91-2764, Albuquerque, NM (1993).
20. ASTM Standards (Electronics II), *Standard Test Method for Interstitial Atomic Oxygen Content of Silicon by Infrared Absorption*, Annual Book of ASTM Standards, ASTM Designation: F 1188, ASTM Committee on Standards, Philadelphia, PA.
21. S. S. Tsao, D. R. Myers, T. R. Guilinger, M. J. Kelly, and A. K. Datye, *Selective Porous Silicon Formation in Buried p+ Layers*, J. Appl. Phys., Vol. 62, p. 4182 (1987).
22. S. S. Tsao, T. R. Guilinger, M. J. Kelly, V. S. Kaushik, and A. K. Datye, *Porous Silicon Formation in n-/n+/n- Doped Structures*, J. Electrochem. Soc., Vol. 138, p. 1739 (1991).
23. M. J. Kelly, T. R. Guilinger, and J. O. Stevenson, *Silicon Micromachining Based on Porous Silicon Formation*, Ext. Abstracts of the 180th Meeting of the Electrochem. Soc., Vol. 91-2, Abs. 355 (1991).
24. H. Tsuya, M. Kanamori, M. Takeda, and K. Yasuda, *Infrared Optical Measurement of Interstitial Oxygen Content in Heavily Doped Silicon Crystals*, VLSI Science and Technology/1985, Edited by W. M. Bullis and S. Broydo, Vol. PV85-5, p. 517, The Electrochem. Soc., Pennington, NJ (1985).
25. A. Baghdadi, W. M. Bullis, M. C. Croarkin, Yue-zhen Li, R. I. Scace, R. W. Series, P. Stallhofer, and M. Watanabe, *Interlaboratory Determination of the Calibration Factor for the Measurement of the Interstitial Oxygen Content of Silicon by Infrared Absorption*, J. Electrochem. Soc., Vol. 136, p. 2015 (1989).
26. W. P. Dumke, *Quantum Theory of Free Carrier Absorption*, Phys. Rev., Vol. 124, p. 1813 (1961).
27. B. Jensen, *Handbook of Optical Constants of Solids*, Edited by E. D. Palik, Chap. 9, Academic, Orlando, FL (1985).

28. A. Borghesi, Chen Chen-Jia, G. Guizzetti, F. Marabelli, L. Nosenzo, E. Reguzzoni, and A. Stella, *Infra-Red Properties of Bulk Heavily Doped Silicon*, Nuovo Cimento, Vol. 5D, p. 292 (1985).
29. A. Borghesi, P. Bottazzi, G. Guizzetti, L. Nosenzo, and A. Stella, *Fundamental Optical Properties of Heavily-Boron-Doped Silicon*, Phys. Rev., Vol. B36, p. 9563 (1987).
30. D. E. Aspnes, A. A. Studna, and E. Kinsbron, *Dielectric Properties of Heavily Doped Crystalline and Amorphous Silicon from 1.5 to 6.0 eV*, Phys. Rev., Vol. B29, p. 768 (1984).
31. D. E. Hill, *Determination of Interstitial Oxygen Concentration in Low-Resistivity n-type Silicon Wafers by Infrared Absorption Measurements*, J. Electrochem. Soc., Vol. 137, p. 3926 (1990).

Figure 1. SE thinning electrochemical cell

Figure 2. SE thinning process flow

Figure 3. PS formation rate for heavily doped n-type silicon

Figure 4a. Typical transmittance spectrum

Figure 4b. Typical absorbance spectrum

Figure 5. Determination of T_{peak} and T_{base} in STM

Figure 6. Baseline comparison of STM and SBT

Figure 7a. Original spectra in transmittance vs. wavenumber domain

Figure 7b. Domain transformation to absorption coefficient vs. wavelength²

Figure 8. Determination of AC_{peak} in CBT

Figure 9a. Correction for background absorption by excluding central portion of spectra from polynomial fit

Figure 9b. Determination of AC_{base} in CBT

Figure 10. Baseline comparison of STM, SBT, and CBT

TECHNIQUE : STM
INPUT FILE : VCLSAM.axy
THICKNESS : .04990 cm

WAVENUMBERS : 960 1040
1200 1300
1102 1112

BASELINE
Transmittance .41208
Wavenumber 1106.94000
Absorp Coeff 4.63950

PEAK
Transmittance .32986
Wavenumber 1106.94000
Absorp Coeff 8.70221

Full Width at Half Maximum 36.64099
Net Absorption Coefficient 3.56271

OLD ASTM (calibration = 9.63, 4.81E+17)	
Inter Oxygen Conc, ppma	34.30892
Inter Oxygen Conc, atoms/cc	1.71366E+18
DIN/NEW ASTM (calibration = 4.90, 2.45E+17)	
Inter Oxygen Conc, ppma	17.45729
Inter Oxygen Conc, atoms/cc	8.72865E+17
IOC-88 (calibration = 6.28, 3.14E+17)	
Inter Oxygen Conc, ppma	22.37384
Inter Oxygen Conc, atoms/cc	1.11869E+18
JEIDA (calibration = 6.06, 3.03E+17)	
Inter Oxygen Conc, ppma	21.59004
Inter Oxygen Conc, atoms/cc	1.07950E+18

Table 1. SiFTIR© output for STM

TECHNIQUE : SBT
 FZ INPUT FILE : vfr3.prs
 FZ THICKNESS : .04990 cm

WAVENUMBERS : 1037 1040
 1232 1241
 1103 1111

CZ INPUT FILE : cal14.jcp
 CZ THICKNESS : .04990 cm

Base1 Corrected Absorbance .22485
 Base2 Corrected Absorbance .21345
 Peak Corrected Absorbance .43114

Base1 Absorption Coefficient 4.50599
 Base2 Absorption Coefficient 4.27757
 Peak Absorption Coefficient 8.64000

OLD ASTM (calibration = 9.63, 4.81E+17)
 Inter Oxygen Conc, ppm 36.43419
 Inter Oxygen Conc, atoms/cc 1.81982E+18

DIN/NEW ASTM (calibration = 4.90, 2.45E+17)
 Inter Oxygen Conc, ppm 18.53869
 Inter Oxygen Conc, atoms/cc 9.26934E+17

IOC-88 (calibration = 6.28, 3.14E+17)
 Inter Oxygen Conc, ppm 23.75979
 Inter Oxygen Conc, atoms/cc 1.18799E+18

JEIDA (calibration = 6.06, 3.03E+17)
 Inter Oxygen Conc, ppm 22.92744
 Inter Oxygen Conc, atoms/cc 1.14637E+18

SAMPLE INPUT FILE : vclsam.axy
 SAMPLE THICKNESS : .04990 cm

OLD ASTM (calibration = 9.63, 4.81E+17)
 Inter Oxygen Conc, ppm 35.49058
 Inter Oxygen Conc, atoms/cc 1.77269E+18

DIN/NEW ASTM (calibration = 4.90, 2.45E+17)
 Inter Oxygen Conc, ppm 18.05855
 Inter Oxygen Conc, atoms/cc 9.02927E+17

IOC-88 (calibration = 6.28, 3.14E+17)
 Inter Oxygen Conc, ppm 23.14443
 Inter Oxygen Conc, atoms/cc 1.15722E+18

JEIDA (calibration = 6.06, 3.03E+17)
 Inter Oxygen Conc, ppm 22.33363
 Inter Oxygen Conc, atoms/cc 1.11668E+18

Table 2. SiFTIR© output for SBT

TECHNIQUE : CBT
 INPUT FILE : VCLSAM.axy
 THICKNESS : .04990 cm

WAVENUMBERS : 1000 1040
 1220 1300
 1103 1111

BASELINE
 Wavenumber 1106.94000
 Absorp Coeff 4.48988

PEAK
 Wavenumber 1106.94000
 Absorp Coeff 8.63474

Net Absorption Coefficient 3.64486

OLD ASTM (calibration = 9.63, 4.81E+17)	
Inter Oxygen Conc, ppma	35.09998
Inter Oxygen Conc, atoms/cc	1.75318E+18
DIN/NEW ASTM (calibration = 4.90, 2.45E+17)	
Inter Oxygen Conc, ppma	17.85980
Inter Oxygen Conc, atoms/cc	8.92990E+17
IOC-88 (calibration = 6.28, 3.14E+17)	
Inter Oxygen Conc, ppma	22.88971
Inter Oxygen Conc, atoms/cc	1.14449E+18
JEIDA (calibration = 6.06, 3.03E+17)	
Inter Oxygen Conc, ppma	22.08784
Inter Oxygen Conc, atoms/cc	1.10439E+18

Table 3. SiFTIR© output for CBT

WELL-RESOLVED PEAKS

(Borderline lightly/heavily doped silicon and Nicolet 60SX spectrometer)

All O_i calculations based on IOC-88 calibration factor of 6.28

FTIR (ppm)		
STM	SBT	CBT
19.8	18.8	17.9
18.9	18.5	17.7
19.4	18.9	18.5
19.2	19.6	18.8
18.8	18.9	18.6
<u>19.6</u>	<u>19.4</u>	<u>18.8</u>
19.3±0.4	19.0±0.4	18.4±0.5

Table 4. O_i measurement reproducibility with well-resolved peaks. Wafer was 0.0304 Ω-cm n-type and 252 μm thick (after SE thinning). Uncertainties are the standard deviation. SIMS measurement on one location of the wafer: 19.9±0.1 ppm O.

POORLY-RESOLVED PEAKS

(Heavily doped silicon and Nicolet 60SX spectrometer)

All O_i calculations based on IOC-88 calibration factor of 6.28

	FTIR (ppm)	
STM	SBT	CBT
21.7	16.1	16.0
24.7	18.3	16.6
22.6	17.3	16.2
21.6	16.0	14.9
26.3	18.2	16.9
<u>23.2</u>	<u>16.7</u>	<u>16.3</u>
23.4±1.8	17.1±1.0	16.2±0.7

Table 5. O_i measurement reproducibility with poorly-resolved peaks. Wafer was 0.0138 Ω -cm n-type and 161 μ m thick (after SE thinning). Uncertainties are the standard deviation. SIMS measurement on one location of the wafer: 17.7±0.2 ppm O.

LIGHTLY DOPED SILICON

(Nicolet 60SX spectrometer)

All O_i calculations based on IOC-88 calibration factor of 6.28

Wafer #	Thickness (um)	Resistivity (Ω-cm)	Type	FTIR (ppm)			SIMS (ppm)
				STM	SBT	CBT	
14242	499	2.40	p-	21.4±0.4	21.7±0.4	21.8±0.5	21.3±0.6
34222	478	13.15	p-	18.0±0.4	18.5±0.4	18.3±0.5	18.4±0.3
13232	438	21.60	p-	19.7±0.4	20.3±0.4	20.4±0.5	21.3±0.2
05222	471	16.94	p-	15.1±0.4	15.3±0.4	15.9±0.5	17.6±0.6
LOO2	598	6.44	p-	12.5±0.4	13.3±0.4	12.3±0.5	13.9±1.1
FZ1	500	>100	n-	0.8±0.4	0.7±0.4	2.2±0.5	1.1±0.3
DSP1*	485	2.26	p-	21.6±0.4	20.9±0.4	21.2±0.5	22.5±0.1

* double-side polished

Table 6. O_i results using only lightly doped silicon. Uncertainties are the standard deviation.

HEAVILY DOPED SILICON

(Nicolet 60SX spectrometer)

All O_i calculations based on IOC-88 calibration factor of 6.28

Wafer #	Thickness (um)	Resistivity (Ω-cm)	Type	FTIR (ppm)			SIMS (ppm)
				STM	SBT	CBT	
P101	390	0.0089	p+	20.1±1.8	16.2±1.0	15.9±0.7	17.3±0.1
14321*	125	0.0143	n+	16.3±1.8	14.8±1.0	14.7±0.7	15.3±0.3
HO21*	125	0.0170	n+	22.0±1.8	17.5±1.0	17.1±0.7	21.9±0.2
MO21*	125	0.0160	n+	22.8±1.8	19.5±1.0	18.8±0.7	19.6±0.2
DSP2†	125	0.0170	n+	21.4±1.8	15.3±1.0	15.2±0.7	16.4±0.3
SB4	161	0.0138	n+	23.4±1.8	17.1±1.0	16.2±0.7	17.7±0.2
3043‡	252	0.0304	n	19.3±0.4	19.0±0.4	18.4±0.5	19.9±0.1

* received thermal processing

† mechanically thinned, double-side polished

‡ borderline lightly/heavily doped

Table 7. O_i results using only heavily doped silicon. Uncertainties are the standard deviation. All wafers except DSP2 were SE thinned.

DISTRIBUTION:

2	AT&T Bell Laboratories Attn: Dr. Wen Lin (1) Dr. Paul Langer (1) 555 Union Blvd. Allentown, PA 18103	1	MS 1056	B. L. Doyle, 1111
		1	MS 1056	C. H. Seager, 1111
		1	MS 1056	H. J. Stein, 1111
		1	MS 0350	S. M. Myers, 1112
		1	MS 0344	T. M. Mayer, 1114
		1	MS 1079	P. S. Peercy, 1300
2	Materials and Metrology Attn: Dr. Murray Bullis 1477 Enderby Way Sunnyvale, CA 94087-4015	1	MS 1082	R. S. Blewer, 1305
		1	MS 0603	J. Y. Tsao, 1311
		1	MS 1078	H. T. Weaver, 1321
		1	MS 1084	R. V. Jones, 1323
		1	MS 1084	H. D. Stewart, 1324
2	SEMATECH Attn: Dr. Howard Huff 2706 Montopolis Dr. Austin, TX 78741	1	MS 1083	P. S. Winokur, 1332
		15	MS 1083	J. W. Medernach, 1332
		1	MS 0342	M. J. Kelly, 1824
		1	MS 0609	A. J. Hurd, 1841
		1	MS 0609	T. R. Guilinger, 1841
1	University of New Mexico Attn: Dr. D. Kendall EECE Department Albuquerque, NM 87131	25	MS 0609	J. O. Stevenson, 1841
		1	MS 0752	P. A. Basore, 6219
		1	MS 0752	W. K. Schubert, 6219
		1	MS 9018	Central Tech Files, 8523-2
		5	MS 0899	Tech Library, 13414
2	Motorola Inc. Attn: Dr. Herng-Der Chiou Electronic Materials Operation 5005 E. McDowell Road Phoenix, AZ 85008	1	MS 0619	Tech Publications, 12613
		2	MS 0100	Document Processing for DOE/OSTI, 7613-2
1	Dr. George Fieg, President Unisil Corporation 405 National Avenue Mountain View, CA 94043			
1	Mr. Thomas Gentemann Unisil Corporation 405 National Avenue Mountain View, CA 94043			
1	Dr. Fritz Kirsch Siltec Silicon 1351 Tandem Avenue P.O. Box 7748 Salem, OR 97303-0139			
1	Dr. Walt Kasianchuk Vice President Engineering & Technology Siltec Silicon 1351 Tandem Avenue P.O. Box 7748 Salem, OR 97303-0139			