APPENDIX I

WORKSHOP AND PANEL DISCUSSIONS

The material presented in this appendix has been written by W. Murray Bullis for Precipitation Effects, Oxygen and Carbon in Silicon and by James R. Ehrstein for Dopant Profiling. It is based on their best recollections. The material did not go through the review process and is presented for information only.

1. WORKSHOP ON PRECIPITATION EFFECTS, OXYGEN AND CARBON IN SILICON

Chairmen: Aslan Baghdadi, National Bureau of Standards, Gaithersburg, Maryland, and

W. Murray Bullis, Siltec Corporation, Mountain View, California.

The workshop on Precipitation Effects, Oxygen and Carbon in Silicon covered a variety of topics with emphasis on oxygen control and measurement. There were five informal presentations, each followed by a lively discussion.

1. ASTM OXYGEN PRECIPITATION EXPERIMENT - R.B.Swaroop, Fairchild Semiconductor.

The objective of this experiment, being carried out by a task force of ASTM Subcommittee F1.04 on Semiconductor Physical Properties, is to establish a simple procedure to enable prediction of precipitation effects of silicon wafers. Six wafer suppliers provided both n- and p-type wafers which covered a wide range of oxygen content. Two thermal cycles were used in the initial phase of the work: A - 1050°C for 16 h; and B - 750°C for 4 h followed by 1050°C for 16 h. Oxygen content was measured before and after the heat treatments by three laboratories; heat treatments were carried out at two locations, and the same three laboratories measured the oxygen content after the heat treatments.

There was a greater scatter in the change of oxygen content following the A cycle; nearly all wafers, regardless of supplier, followed the same characteristic curve following the B cycle. The oxygen and oxygen change measurements showed significant laboratory-to-laboratory differences, but the characteristic shapes of the observed curves were similar. The greatest variations from one sample to another were observed to occur in the mid range of oxygen content. A more detailed report of the experiment is planned for the October 1986 meeting of The Electrochemical Society [1], and a complete publication is planned for the Spring of 1987 [2].

In the discussion which followed the presentation the following points were brought out:

a. Generally similar results were reported to have been observed at several locations.

b. The desirability of being able to use a shorter test cycle was pointed out.

c. Other, more complex, test cycles might be expected to yield somewhat different results.

d. In earlier work [3], a correlation between the results obtained following the two-step cycle (cycle B) and those following a full CMOS simulation was observed.

e. The 4-h nucleation cycle at 750°C overwhelms the prior thermal history of the wafer; if shorter times at 750°C are used, wafer-to-wafer differences in the precipitation characteristics due to thermal history would be more evident.

2. GRAND ROUND ROBIN IN OXYGEN IN SILICON - R.I. Scace, National Bureau of Standards.

The experimental phase of the world-wide experiment to determine the value and reliability of the calibration factor which relates the oxygen content in silicon (in parts per million atomic or ppma) to the infrared absorption coefficient (in cm^{-1}) at 1107 cm^{-1} was reported to be nearly complete. In the past, values differing by nearly a factor of two have been adopted in various ASTM and other standards. Recent publications report values in a much narrower range: 5.4 to 6.4 ppma/cm^{-1} .

This experiment, begun in the summer of 1985, involves representatives of all organizations which have recently reported values for this calibration factor. Its purposes are to determine the best value for this factor and the reliability with which it can be determined. In addition, a broad base of data regarding the reproducibility of infrared determinations of oxygen content is being developed. A more detailed report of the experimental design may be found elsewhere [4]; at this writing (August 1986), the analysis is not complete so the results cannot be reported. The value, when determined will be included in a revision to ASTM Test Method F 121 for Interstitial Atomic Oxygen Content of Silicon by Infrared Absorption.

The discussion following this presentation revolved around the issue of entering and analyzing all the data obtained without introducing errors in the data; consistency checks are being applied to assure the greatest possible data integrity.

3. ANALYSIS OF INFRARED SPECTRA BY A MULTI-COMPONENT LINEAR REGRESSION TECHNIQUE - R. W. Series, Royal Radar and Signals Establishment.

A curve fitting technique [5] for analyzing the infrared spectra of oxygen- and carbon-containing silicon was described. This technique can be applied to product wafers with a variety of back surface characteristics. It requires calibration by the use of standard wafers with known oxygen and carbon content and two polished surfaces.

Rough back surfaces are assumed to scatter only the tranmitted beam. If appropriately small baseline intervals are taken, interference from most overlapping precipitate bands can be avoided. For the 1107 cm^{-1} oxygen band the appropriate interval is 1130 to 1080 cm^{-1}. The 515 cm^{-1} oxygen band does not suffer from interferences from precipitate bands, but it is not suitable for use on thin samples because of interference fringes from multiple reflections. The resolution used in measuring the carbon band in thin samples must be chosen carefully to avoid too much broadening on the one hand and interference fringes on the other; a resolution of 5 cm^{-1} was found to be optimum.

Questions during the discussion brought out the fact that measurements could be made by this technique on samples with background transmittance as low as 1.0 %; measurements have been made with degraded accuracy on very low resistivity (0.03 ohm.cm) antimony-doped samples which had transmittance of 0.1 %.

4. EVIDENCE ASSOCIATING THE 515 CM^{-1} BAND WITH SUBSTITUTIONAL OXYGEN - W. C. O'Mara, Aeolus Laboratories.

Comparison of the vibration frequencies for various isotopes of oxygen, carbon, and boron were used to support the idea that the 515 cm^{-1} band is associated with substitutional rather than interstitial oxygen. The discussion was an extension of a previously published paper [6].

5. SOME OBSERVATIONS ON OXYGEN PRECIPITATION - N.Inoue Nippon Telegraph and Telephone.

Intrinsic gettering was observed to inhibit carrier lifetime degradation due to reactive ion etching. It was also emphasized that the precipitate density, not simply the change in interstitial oxygen concentration, is an important measure of precipitation. Precipitate measurable change of interstitial oxygen concen- tration. Precipitate densities were measured by concentration.Precipitate densities were measured by Wright etching and by transmission electron microscopy. It was found that the morphology of the precipitates depends on the ratio of the nucleation temperature to the growth temperature. A two-step low-high, cycle results in platelets, while a single high temperature treatment results in octrahedral precipitates.

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[5] R.W.Series and F.M.Livingston, Measurement of Interstitial Oxygen and Substitutional Carbon in Silicon, Presented at The Electrochemical Society Meeting, Boston, Massachusetts, May 1986.

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2. WORKSHOP ON DOPANT PROFILING

Chairmen: James R. Ehrstein, National Bureau of Standards, Gaithersburg, Maryland, and

Marek Pawlik, GEC Research Wembley, Middlesex, U.K.

The intended goals of this workshop were to identify the strong and weak points of the available profiling techniques and their relative suitability for various applications. The workshop was structured around a guided discussion which relied heavily on input from the audience as well as the more traditional exchange between the audience and the speakers from the technical sessions of the symposium. The discussion was guided toward obtaining answers to the stated goals by identifying the profiling applications and needs of the audience as well as some of the difficulties and uncertainties that have been experienced. While reasonable success was obtained in identifying relative strong and weak points of the various techniques, developing a definitive statement of suitability for various applications proved elusive; enough considerations were presented to allow most of the audience to make better informed choices in their future work.

Among the strong and weak points of the various profiling techniques, some of which were widely recognized, others not so well appreciated, are the following:

1. SIMS

This technique has been demonstrated to be amenable to very good precision both within and between laboratories, it does not require electrical activation and can therefore be applied both before and after annealing of ion implants to monitor diffusion, it provides an analysis of the dopant distribution which is of primary interest in process modeling, it has reasonable dynamic range for all common dopants; however, the dynamic range obtainable is a function of dopant species - only for the case of boron is it likely to yield data for a complete profile, the primary limitation on SIMS analysis is likely to be due to sputter crater nonuniformity, sputter redeposition or kinematic knock-on can cause profile shape distortion although this appears to be a negligible effect on boron, quantification of the dopant profile from raw data may be limited by inavailability of suitable reference standards or by inaccuracies of ion implant dose values when such dose values are used to normalize SIMS data, finally, obtaining meaningful values of dopant density at the silicon surface is difficult for some SIMS instruments when there is an oxide cap over the silicon.

2. RUTHERFORD BACKSCATTER

It is a nondestructive measurement and analysis is possible from first principles without use of a reference specimen, like SIMS, it responds to dopant density; however, it is primarily applicable to dopants with a noticeably different atomic mass than silicon and even for these it is limited to fairly high concentrations.

3. SPREADING RESISTANCE AND INCREMENTAL SHEET RESISTANCE

Dynamic range does not depend on dopant species, incremental sheet resistance can profile nearly to a junction while spreading resistance can profile through one or more junctions, both provide information on electrical activation which is an important consideration for novel process development, both can give evidence of electrically active material defects although the interpretation may not be straightforward; both techniques average over a depth below the point of measurement and hence the data must be deconvolved in order to calculate a depth distribution - the deconvolution procedure is relatively straightforward for incremental sheet resistance and relatively complicated for spreading resistance, the profiles directly derived from these measurements are for resistivity or conductivity - as a result the free carrier density profiles cannot be uniquely extracted unless the carrier mobility function is reasonably well known - this may not be the case for novel fabrication procedures, the deconvolution procedures make these techniques highly sensitive to measurement noise, for submicron structures for free carrier concentrations may be displaced from the dopant distribution due to carrier spilling particularly in the tail of the profile - it does not appear possible to work backwards in a unique fashion to calculate the dopant distribution from the carrier distribution.

4. CAPACITANCE - VOLTAGE MEASUREMENTS

This technique is without parallel for profiling lightly doped material, diode-, MOS-, and Schottky-CV measurements allow compatibility with virtually any process being developed; however, it has limited dynamic range due to voltage breakdown, diode and Schottky structures will not allow profiling close to the surface, MOS structures will allow profiling near the surface but results may be degraded by oxide and interface states; for best accuracy, a number of corrections may have to be applied.

DISCUSSION

All these techniques suffer from the limitation of being vertical profilers - none is capable of determining lateral spread of dopants under a mask edge - an area of increasing importance.

An important output of the discussion was the recognition that while precision is the primary requirement for any of the techniques to be acceptable, an understanding of the underlying accuracy of the various techniques as well as the procedures necessary for realizing that accuracy is increasingly important - primarily for process development applications, but also for process control. Discussion of measurement accuracy occupied a significant portion of the workshop. It was noted that, while progress has been made on all techniques, assessing the accuracy of any of them is difficult since each measures a somewhat different characteristic of the dopant profile.

Comparison studies which have attempted to study the relation between different measurements have generally confirmed the theoretical prediction that carrier spilling will cause the dopant profile determined by SIMS to have a deeper tail than the carrier profile determined by spreading resistance. Yet the several reported studies of this type give somewhat different quantitative comparisons. How much of this variability is due to the quality of the measurements and how much is due to differences in the specimens used is not known. One set of boron implant data used to illustrate the results of several profiling techniques resulted in an interesting comment. One researcher in the audience observed that he originally had done most of his original profiling work by CV technique, but now he had become convinced that SIMS was the technique of choice for accuracy; however, for the data being presented, he considered the spreading resistance, not SIMS, profiles to be "correct", because the spreading resistance gave the "right" shape for the profile tail. Another person pointed out that it may be misleading to attempt to verify the accuracy of profile measurements by comparison with the predictions of a processing model such as SUPREM since SUPREM II is heavily tied to spreading resistance measurements as an input, while SUPREM III is heavily tied to SIMS measurements. Evaluation of profiling measurements was thus seen to be somewhat circular. Since there is no fully independent starting point, the physics of the measurements and that of the sample fabrication are intertwined. It is tempting to evaluate the quality of the measurement by what is thought to be known from the models for such processes as implantation, annealing and diffusion; but the models rely on measurements for verification and refinement.

CONCLUSIONS

The conclusions of the workshop were that certain limitations are known for each of the techniques; while some may be minimized by improvements in technique or theory, others, such as carrier-spilling and debye-length limitations, are fundamental. The available techniques were seen to be complementary, rather than competing. Adequate attention to the known limitations may allow a single technique to be used satisfactorily for process control applications. However, the use of two or more techniques will continue to be necessary to improve the understanding of the physics of sample processing steps as well as the physics of the measurements themselves.

APPENDIX II

GRADUATE EDUCATION FOR THE ELECTRONICS INDUSTRY

Pat Hill Hubbard

[The material presented in this appendix did not go through the review process and is presented for information only. It was prepared by Dinesh C. Gupta, Co-Editor from the recordings of the presentation and the excerpts provided by P. Hubbard.]

American Electronics Association, four years ago, launched a program, through its Electronics Education Foundation, to improve the faculty shortages in electrical and computer engineering - viewed as a major bottleneck to a steady and sufficient supply of graduates. Determining that the faculty vacancies were primarily caused by the fact that U.S. citizens with BS degrees prefer industry salaries rather than four to five years of costly doctoral study for an end goal of an academic career with uncompetitive teaching salaries, the Foundation began a national program to make a doctoral study and academic careers more attractive.

A cornerstone to these efforts is the fellowship-loan program. American Electronic Association [AEA] companies are currently supporting 136 U.S. citizens who want to get Ph.D.s and teach - each at a four-year cost to a company of $76,000 at a private and $52,000 at a public University. Nationally, latest data on engineering faculty showed a faculty vacancy rate of 8.5 % [1983] - an alarming figure since enrollments have increased 100 percent over the past decade and new faculty only 10 percent. California is a prime producer of electrical and computer engineers but it produces only one-fourth EE/CE Ph.Ds. annually. This information was the result of a survey of all California public and private colleges which offer EE/CE programs. Other interesting data from this survey are given below.

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- o In 1984, California ranked first among the states in numbers of graduating BS in EE and CE.

- o California's engineering faculty vacancy rate in 1985 was 22 percent or 470 of 2160 full-time equivalent engineering faculty [FTEF] positions were vacant.

- o Seventy-seven percent or 362 FTEF vacancies in California engineering schools are filled by 1286 part-time faculty, leaving 23 percent of the remaining authorized FTEF unfilled.

- o California engineering schools will lose 178 full-time faculty members or 10.5 percent of the 1690 current full-time faculty over the next five years. About 83 percent of these will retire.

- o In the last three years, for every 2 full-time tenure track engineering faculty which have been hired in California, one faculty member has been lost, mostly through retirement. The state is expected to lose, in the next five years, about 11 percent of its full-time engineering faculty members, again, mostly through retirement.

- o By 1990, California engineering schools will need to hire 648 new or 30 percent of their current full-time faculty equivalent, just to maintain today's enrollment and the highest level of quality education.

The need to have an adequate supply of quality engineers and sufficient faculty to educate them is considered of paramount importance to the health of the U.S. high tech industry and to the economic health of the nation.

Where is our future faculty to come from?

A major cause of the faculty shortage is that U.S. citizens with B.S. degrees avoid Ph.D. programs and teaching careers in favor of industry salaries. Foreign-born Ph.Ds. remain the major faculty hiring source. Nationally, 39 percent of all engineering Ph.Ds. awarded in the U.S. in 1983-84 went to foreign nationals (all non-U.S. citizens except permanent resident aliens). More than one-fourth (26 percent) of all assistant engineering professors did not receive B.S. degrees from a U.S. university. There are a few other interesting facts. 1. In 1984, one-half to three-quarters of engineering job applicants at Rose-Hulman Institute of Technology were foreigners. 2. Forty-nine percent of the new tenure tract faculty hired in 1983 at the nine California State University engineering departments in the last five years were foreigners and fifty-six percent of electrical and computer engineering faculty new hires were foreigners. 3. Thirty-six percent or 115 of the 322 newly hired full-time faculty over the last three years graduated from a foreign high school or college. While the hiring of foreign nationals may be controversial because foreigners may not communicate well in the classroom due to their English-accent, engineering deans are often faced with a contemporary Hobson's Choice that means either filling a vacancy or leave it as a vacancy.

Nationally, only 693 Ph.Ds. in electrical engineering were awarded by U.S. universities in 1984. This is seven fewer than were awarded in 1974. Sixty fewer computer engineering Ph.Ds. were awarded in 1984 than in 1979, although total CE enrollment doubled during this period. Seventy two percent of U.S. engineering deans indicated the most significant problem in attracting U.S. BS degree graduates to doctoral study was the insufficient funding for graduate student support.

To date, AEA companies have pledged $10 million to support 136 fellowship-loans for U.S. citizens around the country. The program that American Electronics Association launched in order to meet and overcome faculty shortage problem is doing very well.