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Measurement Techniques for High-Resistivity Detector-Grade Silicon: Progress Report, July 1, 1982 to June 30, 1983

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Semiconductor Materials and Processes Division
Washington, DC 20234

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Prepared for
Electronics Technology and Devices Laboratory
Fort Monmouth, New Jersey 07703

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MEASUREMENT TECHNIQUES FOR HIGH-RESISTIVITY DETECTOR-GRADE SILICON: PROGRESS REPORT, JULY 1, 1982 TO JUNE 30, 1983

R. D. Larrabee and J. R. Lowney

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This is a progress report. The work is incomplete and is continuing. Results and conclusions are not necessarily those that will be included in the final report.

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

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PREFACE

This work was conducted as part of the Semiconductor Technology Program at the National Bureau of Standards (NBS). This program serves to focus NBS research in areas that enhance the performance and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices. These research programs are designed to produce carefully evaluated and well-documented test procedures and associated technology. The resulting improved measurement technology leads to greater economy in government and industrial procurement by providing a common basis for purchase specifications. This program is conducted in collaboration with industrial and governmental users and suppliers of semiconductor materials and devices and with standardization groups such as the American Society for Testing Materials (ASTM).

The segment of the Semiconductor Technology Program described in this report was partially supported by the Electronics Technology and Devices Laboratory (ET&DL) at Fort Monmouth, New Jersey under their Project No. 82-JAK-06 and NBS Task No. 725-2310. The contract was monitored by Dr. R. L. Ross and R. Savage of ET&DL. The NBS point of contact for information about the technical elements of this project is R. D. Larrabee of the Semiconductor Materials and Processes Division at the National Bureau of Standards.

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ABSTRACT

Techniques for nondestructively characterizing the resistivity and excess-carrier recombination lifetime in ingots of high-resistivity, long-lifetime detector-grade silicon are being evaluated. In particular, three interrelated techniques for nondestructively 1) measuring an average resistivity, 2) profiling the low-level excess-carrier lifetime, and 3) profiling the resistivity of cylindrical ingot specimens are proposed and are in the process of being evaluated. All three techniques treat the ingot under test as a large van der Pauw specimen and require removable silver-paste contacts or pressed-on capacitive contacts. The profiling measurements utilize a highly penetrating 1.15-μm He-Ne laser beam as an optical probe. The conceptual and theoretical background for these measurements and the results of feasibility experiments obtained to date are presented. These results show the expected behavior and produce reasonable results, but additional work is required to complete the feasibility experiments and to confirm the results on a few specimens by some independent technique.

Key words: detector-grade silicon; lifetime profiling; resistivity profiling; van der Pauw measurements.

I. INTRODUCTION

This project was designed to explore the feasibility and practicality of new or improved measurement techniques for the characterization of high-resistivity, long-lifetime detector-grade silicon. The project is part of the NBS Semiconductor Technology Program and is intended to improve the characterization of detector-grade silicon for applications such as PIN photodiode detectors and CCD imaging arrays. Characterization of this material by conventional techniques provides some measure of material quality, but this may not prove to be the best possible measure for any given device application. The establishment of a series of well-documented characterization techniques specifically designed to suit the intended application and adapted to high-resistivity, long-lifetime material should lead to better control of the significant properties of the starting material and the possibility of higher yield and performance of completed devices. The emphasis of the present work has been on the development of techniques for nondestructively characterizing ingot sections of as-received (as-shipped) silicon prior to any processing except grinding to a cylindrical shape and polishing the ends to facilitate optical probing measurements.

Dark current due to leakage or thermal-generation mechanisms is of prime importance to CCD imaging and signal processing devices and, if large enough, is of interest in PIN photodiode detectors. There are several potential mechanisms of dark-current generation: thermal generation within the depletion region of an MOS capacitor, Schottky barrier device, or p-n junction; diffusion of minority carriers, which were generated elsewhere within the device structure, to this depletion region; and surface-related mechanisms. Therefore, it is inappropriate to characterize even the bulk contributions to dark current by a single parameter. However, the excess-carrier recombination lifetime is sometimes used for this purpose. But insofar as it only characterizes the diffusion of minority carriers to the depletion region (and not thermal generation within the depletion region), it is inadequate. The thermal-generation lifetime within the depletion region [1] is more difficult to measure [2,3], is fundamentally different from the excess-carrier recombination lifetime [1,3-5] and is a necessary parameter for the characterization of the net thermal generation within a device containing a depletion region. Characterization of surface-related leakage mechanisms can be important for fully fabricated devices, but is not apropos to the characterization of as-received ingots. This report will discuss a way to profile nondestructively an axial-average excess-carrier low-level recombination lifetime over the cross section of cylindrical ingots of high-resistivity silicon. At the present time, the authors are not aware of any technique for nondestructively profiling the corresponding axial-average thermal-generation lifetime over the cross section of cylindrical ingots.

The resistivity of as-received ingots can be of prime importance for applications in which the active portion of the device is the depletion region. For a given fixed value of reverse-bias operating voltage, the width of the depletion region is a function of the net doping density. For the high-purity detector-grade silicon of present interest, the room-temperature carrier mobilities are determined by lattice scattering and are virtually independent of the doping density. Under these conditions, the net doping density can be characterized by resistivity measurements.

Although various techniques have been developed for measuring the resistivity of silicon, they are not all applicable to nondestructive measurements on high-resistivity ingot specimens. Probe techniques are commonly used at lower resistivities [6,7] and find extensive application in measuring the axial dependence of the resistivity of as-grown ingots. The four-point probe technique is also used to profile the radial dependence of silicon wafers [6,7]. However, these techniques may become unreliable and unstable at high resistivities due to surface and probe-contact effects and, at best, require extreme care and attention to details. Therefore, alternative approaches have been studied as a replacement for probe techniques or as a means of confirming the results of probe measurements. Contactless magnetic coupling (eddy current) techniques become increasingly insensitive at high resistivities due to the small values of induced current. Increasing the frequency of operation helps in this respect, but is limited by the resulting increases in displacement current. This limits the frequency of operation to a few megahertz for resistivities in the tens of kilohm-cm region, if the silicon specimen is to be modeled as a "pure" resistance. The present experiments with high-resistivity detector-grade silicon have shown greater coupling using capacitive contacting techniques (e.g., ingot specimens placed inside coils interacted through capacitive coupling to the wires of the coil instead of through the coil's ac magnetic field), thus indicating that this is the preferred approach.

This report will discuss resistivity measurements using an ac version of the van der Pauw technique [8,9] with removable silver-paste contacts or with pressed-on capacitive contacts to the lateral surface of cylindrical ingot specimens. This report will also discuss resistivity and lifetime profiling techniques which are extensions of this basic van der Pauw technique and which use the same van der Pauw specimen.

The basic van der Pauw technique assumes a homogeneous specimen resistivity. If the specimen has a small inhomogeneity, the method yields an average value that, in general, does not represent equal contributions from every volume element within the ingot. This "average" ingot resistivity may not be an adequate characterization for those applications that require uniformity for different devices fabricated on the same wafer (e.g., uniformity of depletion-layer depth at a given voltage). For these cases, it would be desirable to profile nondestructively the resistivity of the ingot in order to select those ingots with resistivity variations which are not considered excessive for the intended application. Small resistivity gradients along the ingot length can be measured by cutting the cylindrical ingot into smaller length pieces and measuring the "average" resistivity of each piece by the ac van der Pauw method to be discussed in this report. This report will also discuss an optical-profiling technique that can be applied to these van der Pauw pieces for nondestructively profiling their radial variations in resistivity. Therefore, the combination of cutting into smaller length pieces and of optical profiling allows one to characterize the resistivity variations in three dimensions and thus determine if the variations throughout the entire ingot are acceptable for the intended application. These techniques are based on the assumption that, to a first approximation, the specimens are homogeneous in resistivity and then, as a second approximation, the inhomogeneity is measured against this uniform background.

The three basic characterization techniques to be discussed in this report (i.e., measurement of average ingot resistivity, profiling ingot resistivity, and profiling radial variations of excess-carrier recombination lifetime) can all be performed on the same cylindrical van der Pauw specimen (ingot section) provided with removable silver-paste or pressed-on capacitive contacts. The procedures for these nondestructive measurements and the interpretation of the data obtained are relatively simple and the necessary equipment is not prohibitively expensive. Therefore, it is anticipated that they may find applications for the routine inspection of incoming (or outgoing) material to assure compliance with specifications.

II. MEASUREMENT OF AVERAGE INGOT RESISTIVITY

Figure 1 shows a cylindrical ingot section that has been provided with four linear contacts on its lateral surface to effectively make the entire ingot section into one large van der Pauw specimen [8-10]. In this way, a current I can be passed through two adjacent contacts (labeled 1 and 2 in fig. 1) and the resulting voltage V observed at the remaining two contacts (labeled 3 and

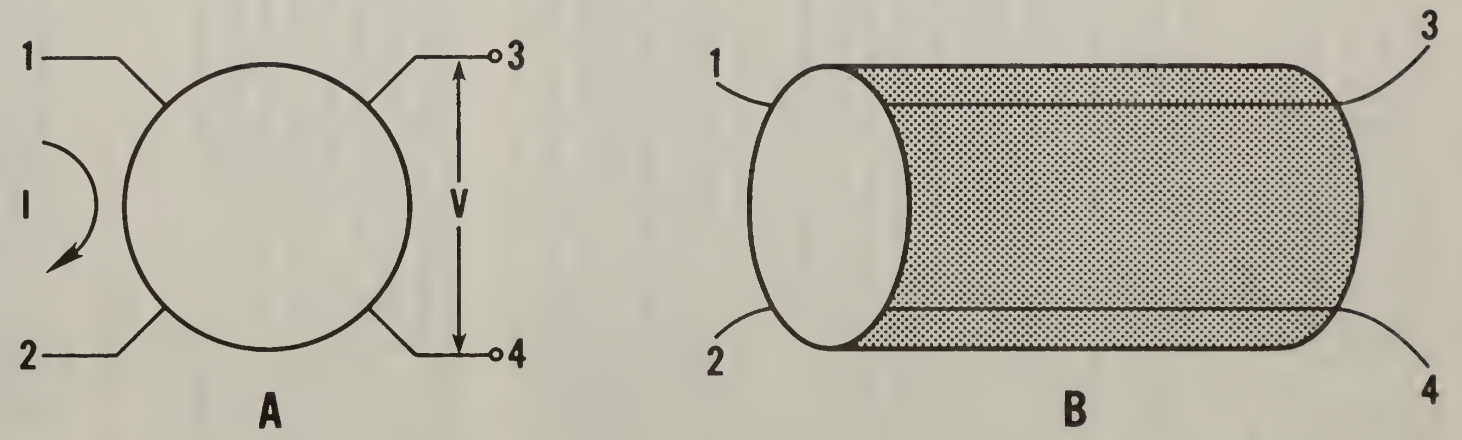

Figure 1. Schematic and pictorial views of a cylindrical ingot specimen provided with four van der Pauw contacts. The contacts are numbered and used as shown for current contacts and voltage probes.

4 in fig. 1). The ingot resistivity ρ is then computed from the well-known van der Pauw relationship [7,10] for this geometry:

$$\rho = \frac{(V/I)\ \pi\ L}{\ln(2)} , \tag{1}$$

where L is the length of the ingot specimen.

The use of this technique on ingot sections instead of wafers not only decreases the potential problems with surfaces (because of the smaller surface/volume ratio), but also permits evaluation of ingot sections before they are cut up into wafers. This technique has been used successfully with dc current and removable silver-paste contacts to an as-ground lateral surface on a 2-in. diameter, 1-in. long silicon ingot with a resistivity of about 50,000 Ω•cm. The slope of the current-voltage characteristic at the origin between any two of the 1-mm wide van der Pauw contacts was about 100,000 Ω. The use of dc techniques with removable silver-paste contacts on an as-ground-and-etched lateral surface remains to be explored.

Pressed-on capacitive contacts offer an attractive possibility but necessitate the use of ac instead of dc. In this case, the reactance of the capacitive contacts must not be so large as to prevent the required current flow and must be small compared to the impedance of the voltage sensing device (to validate the assumption of ignoring the voltage drop across the voltage-sensing contacts). Increasing the frequency of operation lowers the reactance of the contact capacitance, but if the silicon material is to be modeled as a pure resistance, the frequency of operation cannot be so high as to give rise to a significant amount of displacement current. The charge and displacement currents in silicon are equal when $\sigma/\omega\varepsilon = 1$, where σ is the conductivity of the silicon (reciprocal resistivity, ρ), ω is the radian frequency of operation, and ε is the dielectric constant of silicon (1.06×10^{-10} farads/meter). This occurs at a frequency of 15 MHz for 10,000 Ω•cm silicon. Thus, to avoid the necessity of modeling the silicon as a complex impedance, the frequency of operation should be well below this value. Therefore:

$$f \ll \frac{\sigma}{2\pi\varepsilon} = \frac{1}{2\pi\varepsilon\rho} . \tag{2}$$

Some preliminary experiments with capacitive contacts to as-ground surfaces have indicated that a porous deformable conducting material (such as the foam plastic material used to short-circuit the pins of sensitive integrated circuits during shipment or storage) can be cut to the desired shape and pressed against the ingot surface to provide a capacitive contact with a very small external spacing. However, the total dielectric thickness of the contact capacitance also includes any surface depletion layer in the silicon, and it may be necessary to pretreat the surface to a weak accumulation condition to minimize the total effective spacing and thus maximize the effective contact capacitance. In addition, the ac drive should not be so large in amplitude as to produce an appreciable depletion layer at the peak of the voltage cycle. If this occurs, the contact capacitance could become a significant nonlinear element in the circuit. These conditions have been satisfied for capacitive contacts with larger areas than shown in figure 1 for this 50,000

$\Omega\cdot$cm specimen, but the thin linear capacitive contacts of the van der Pauw structure of figure 1 have not yet been studied.

The average resistivity obtained by this van der Pauw technique is not the simple numerical average of the resistivity over the circular cross section because different regions of the circular cross section contribute differently to the "average." However, if the variations in resistivity over the cross section are not large, this "weighted average" can be compared for specimens cut from different positions along the length of the parent ingot and thus give information about any axial variation of resistivity. If the axial variations of resistivity of a single ingot section are significant, each of the four van der Pauw contacts can be broken up into equal length segments and van der Pauw measurements performed on each set of four segments (which then define a smaller length of the ingot specimen). In this case, the same ac (or dc) voltage needs to be applied to each corresponding pair of segmented van der Pauw current contacts to prevent current from flowing axially and thus permit the measurement of the van der Pauw voltage over the uncut portion of the ingot length as if it had been cut out. These axial profiling techniques assume that, to a first approximation, the specimen is homogeneous and that axial variations are measured against this background.

The following sections of this report discuss extensions of this basic scheme to resistivity and lifetime profiling. These profiling techniques use the same van der Pauw ingot section specimen as the present average resistivity technique, and the previous discussion about contacts and frequency of operation also pertains to these profiling measurements.

III. PROFILING EXCESS-CARRIER RECOMBINATION LIFETIME

A chopped 1.15-μm infrared He-Ne laser beam can be passed axially through the ingot specimen of figure 2 to generate electron-hole pairs in the illuminated region. An infrared-transmitting filter is included in the system of figure 2 to remove any visible light from the beam; a neutral-density filter is also included to provide for adjusting the intensity of the beam. The beam is mechanically chopped with a short on-period and a long off-period compared to the excess-carrier recombination time being measured. The laser beam is incident on one of the polished ends of the ingot specimen, and either the specimen or the laser beam is movable so the laser beam can be scanned along a specimen diameter oriented 45 deg with respect to the diameters joining opposite contacts as shown in figure 3. The coordinate x is used to designate the position of the laser beam along this diameter relative to the center of the ingot face. The optical absorption depth of 1.15-μm infrared light is several inches in high-purity silicon, and if the ingot is not too long, laser light can be detected passing out the far end of the ingot as indicated in figure 2. Detection of this light is not necessary for the present purposes, but the transmitted beam should be terminated properly as a safety precaution and to assure that it does not reflect off something and return to the specimen.

The basic physics and geometrical aspects of a circular column of light scanning along a diameter of a much larger cylindrical specimen of semiconductor material have been studied previously by Larrabee and Blackburn [10]. If the quantity ρ in the denominator of eq (8) of that paper is replaced by the

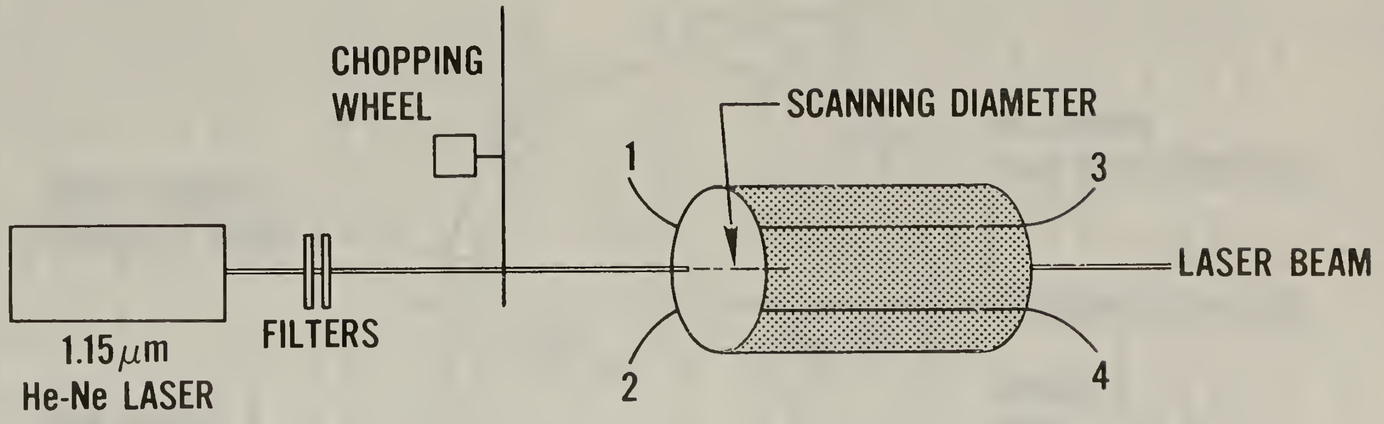

Figure 2. Schematic diagram of the optical portion of the apparatus for profiling excess-carrier recombination lifetime.

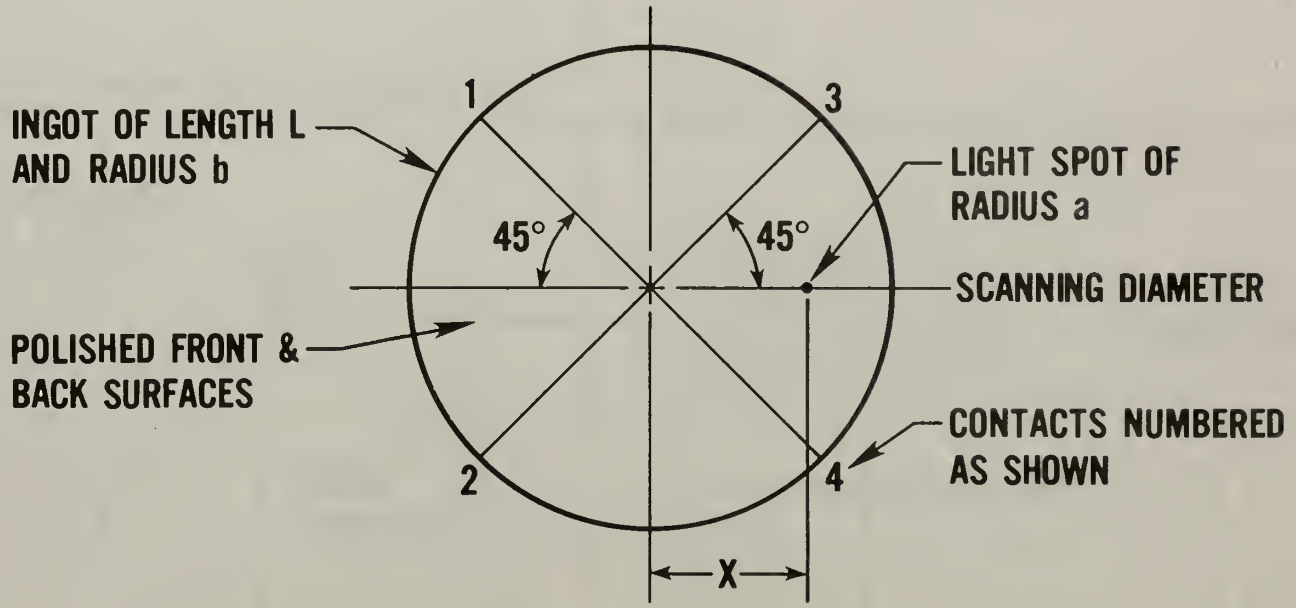

Figure 3. End view of a cylindrical ingot specimen showing the relationship between the scanning diameter and the four van der Pauw contacts.

local resistivity at the light-spot position $\rho(x)$, eq (11) of that paper becomes:

$$\Delta R = \frac{\Delta V_{34}}{I_{12}} = \frac{4a^2b^2\rho_{ave}(\Delta\rho)}{\pi L(2\rho(x) + \Delta\rho)} \; \frac{1}{(b^4 + x^4)} , \tag{3}$$

where the voltage and current subscripts have been changed to the present notation, ρ_{ave} is the average resistivity of the ingot specimen (e.g., measured by the technique discussed in sec. II, above), a is the radius of the laser beam, b is the radius of the ingot specimen, L is the length of the ingot specimen, and $\Delta\rho$ is the change in resistivity caused by photoexcitation of electron-hole pairs by the laser beam. The quantity ρ_{ave} in eq (3) is not taken to be a function of x because this term arose in an expression for an electric field which was integrated to give the voltage distribution over the wafer surface (i.e., eq (3) in ref. 10). Therefore, this resistivity is representative of the whole wafer, whereas the resistivity presently called $\rho(x)$ arose from solving the boundary condition at the light spot position and is therefore characteristic of this particular region of the wafer. ΔV_{34} is the change in van der Pauw voltage at contacts 3 and 4 due to the existence of a $\Delta\rho$ (i.e., due to chopping the laser beam). If $\Delta\rho/\rho_{ave}$ is small, then $\Delta\sigma = -\Delta\rho/(\rho(x))^2$, where $\Delta\sigma$ is the change in conductivity due to the photoexcited carriers. If this expression for $\Delta\sigma$ is substituted into the above equation and the resulting equation solved for the product $(a^2\Delta\sigma)$, one obtains:

$$a^2\Delta\sigma = \frac{\pi L\ (-\Delta R)}{2b^2\rho_{ave}\rho(x)} \left(b^4 + x^4\right) . \tag{4}$$

Consequently, at any given position of the laser beam (i.e., any given value of x), $\Delta R = \Delta V_{34}/I_{12}$ is directly proportional to $\Delta\sigma$. Thus, the variation of the van der Pauw voltage ΔV_{34} for a fixed current I_{12} can be used to monitor directly the changes in $\Delta\sigma$ as the excess photogenerated carriers recombine. Therefore, the transient return of ΔV_{34} to steady-state conditions can be used to measure directly the excess-carrier recombination lifetime at any position x on the scanning diameter in a manner completely analogous to a conventional decay of photoconductivity measurement [11].

Several conditions must be satisfied for this scheme to produce a valid measurement of excess-carrier recombination lifetime. The observed transient return to steady state after the laser light has been chopped off should be exponential. Nonexponentiality could arise from too large a laser light intensity (lifetime varying with excess-carrier density), unequal electron and hole lifetimes (due to selective trapping of one carrier), or multiple recombination centers (giving rise to several distinct mechanisms of recombination with different lifetimes). Since this is essentially a decay of photoconductivity experiment, all the conventional caveats about that technique [11] apply equally well to the present situation. The assumption was made in the derivation of eq (4) that $\Delta\rho/\rho_{ave}$ was small. Therefore, it is necessary to vary the laser light intensity (by using the various neutral density filters) to assure that it is low enough to satisfy this constraint (i.e., measured lifetime does not depend on the light intensity used) and not

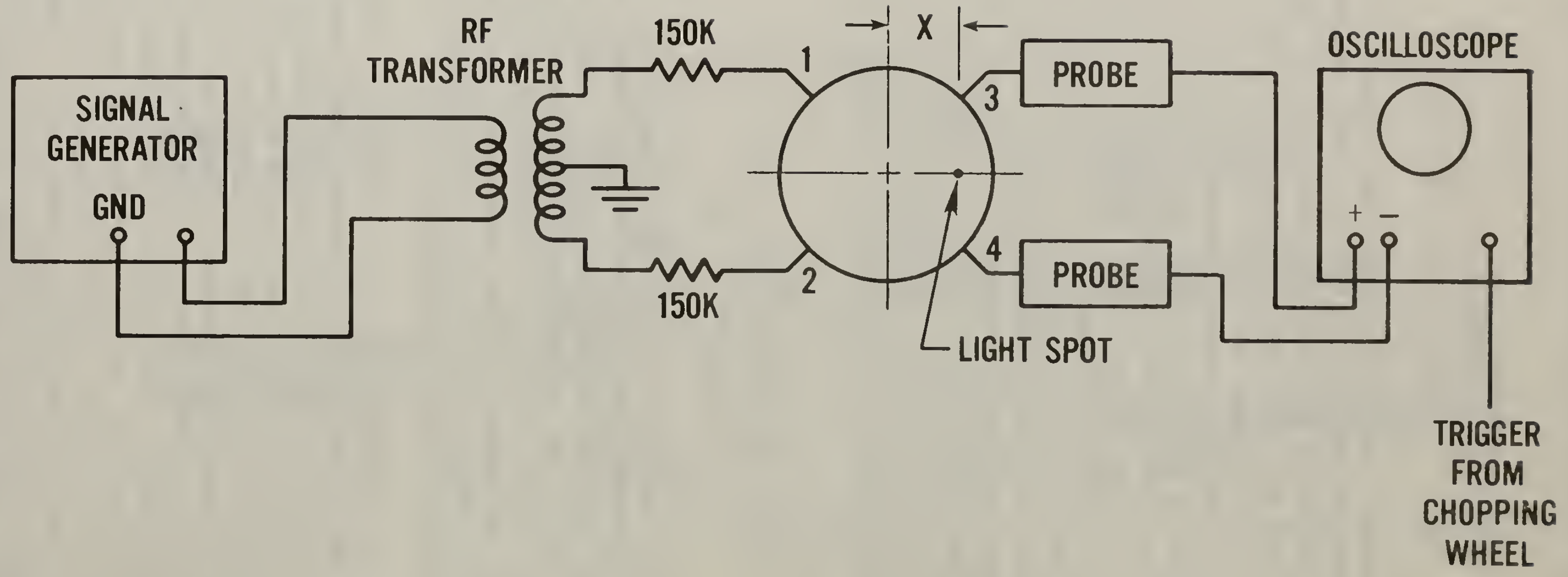

Figure 4. Schematic diagram of the electrical portion of the apparatus for profiling excess-carrier recombination lifetime.

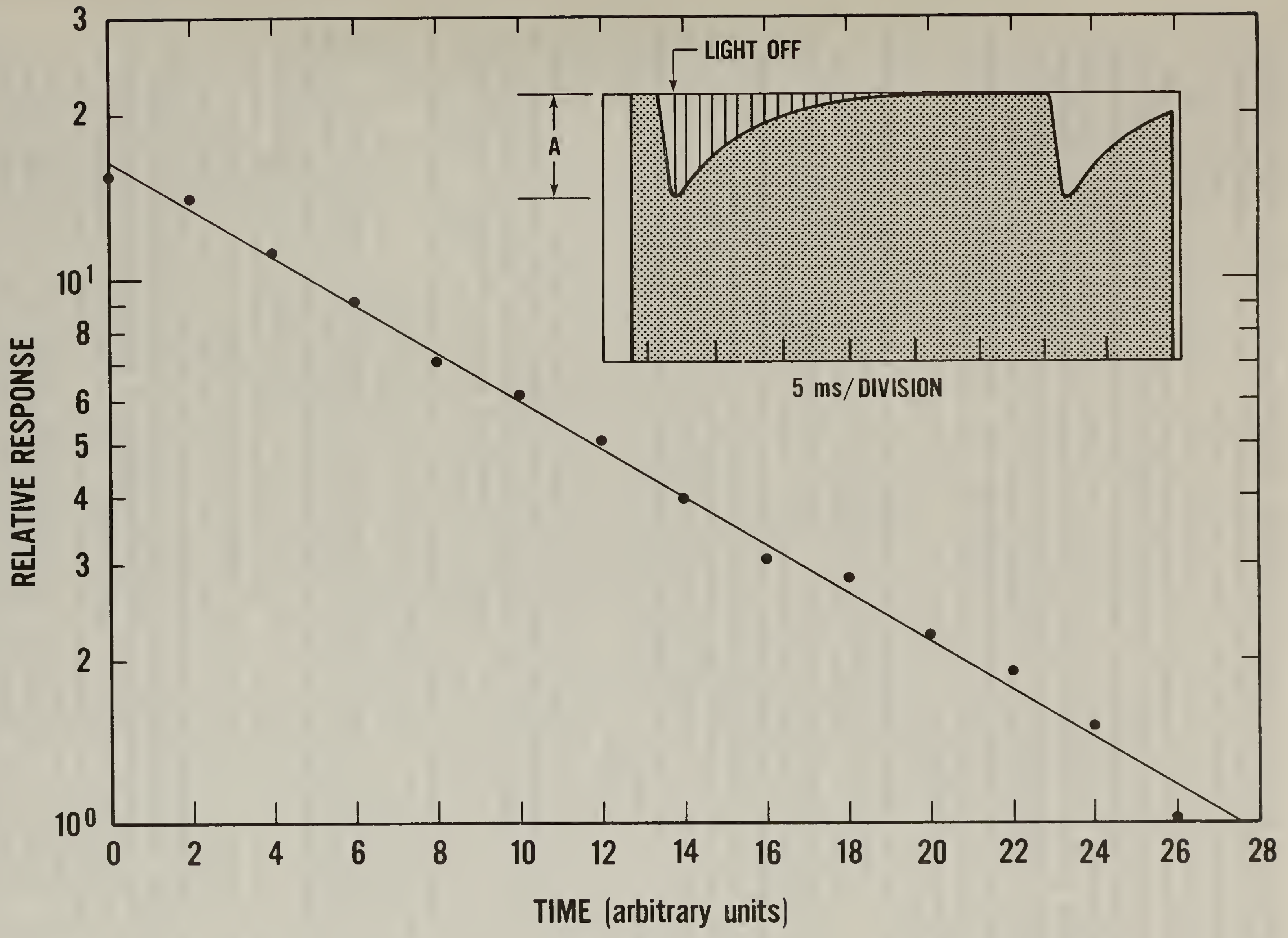

Figure 5. Results of a feasibility experiment to demonstrate the lifetime measurement technique. Insert shows the modulation envelope of the ac van der Pauw voltage during the light-chopping cycle. The graph shows plotted points measured from the modulation envelope and a fitted least-squares line indicating that the decay is exponential and that the lifetime is 4.8 ms.

so high as to produce nonexponentiality. When these conditions are satisfied, the measured lifetime will be the low-injection-level excess-carrier recombination lifetime [4,5].

In addition, it is necessary to use a constant ac current drive (i.e., not dc) to assure that there is no drift of the photoexcited minority carriers out of the region where they were excited (i.e., the laser beam) towards the appropriately biased current contact. The use of ac causes the photoexcited carriers to oscillate about their point of generation without a dc component of drift. The amplitude of the ac drive cannot be so large as to produce a significant amplitude of oscillation compared to the laser-beam radius. However, this is easily checked experimentally by measuring the lifetime as a function of ac drive and the frequency of operation and requiring that it be independent of both.

Thermal diffusion of photoexcited carriers out of their region of photogeneration is certainly a problem if they reach the surface of the cylindrical ingot. However, if the laser beam is kept at least a few diffusion lengths away from the ingot surface, then as the carriers diffuse, the effective size of the region containing the photoexcited carriers increases (i.e., it is no longer equal to the laser radius a). However, if this situation is modeled as an expanding cylindrical region of constant $\Delta\sigma$, then the product $a^2\Delta\sigma$ of eq (4) is not changed by this radial expansion if a is taken as the radius of the expanded region containing the photoexcited carriers. Therefore, the van der Pauw voltage ΔV_{34} still serves the purpose of measuring the recombination lifetime, but over a volume defined by the sum of the laser light radius and the diffusion length.

The laser light is attenuated as it propagates axially through the specimen. This is not a serious limitation in the low-injection regime of interest where the lifetime is not a function of the photoexcited carrier density. However, it does limit the length of ingot that can be measured, and it may be necessary to measure long ingots a second time with the laser light incident from the opposite end. In fact, it may be desirable to do this with the shorter ingots as a check on the validity of the results.

Figure 4 shows the circuit used to test the feasibility of this approach using the 50,000 Ω•cm specimen of silicon discussed in Section II above. The two 150,000 Ω series resistors in the current-drive circuit comprise about 80 percent of the ac circuit resistance and thus effectively give a constant ac current drive characteristic. The voltage-sensing probes are high impedance probes (compared to the specimen impedance between the voltage contacts) so they accurately sense the voltage at the ingot surface at the contact position. The removable silver-paste contacts to an as-ground surface discussed in Section II above were used in this feasibility test, and similar tests with silver-paste contacts to etched surfaces and pressed-on capacitive contacts are planned for future experiments. The results to be presented were not sensitive to the frequency of operation over the range from 200 to 500 KHz, and 300 KHz was used for the results to be reported. The oscilloscope display of the top portion of the modulation envelope of the 300-KHz signal, V_{34}, is shown in the insert of figure 5. The lifetime can be directly observed as the time constant of the exponential decay following the 1-ms illumination period (i.e., on-time of the chopping wheel). The transient was measured at the indicated points and plotted as shown in figure 5 to give a measured lifetime of 4.8 ms. This measurement was performed at the center of the ingot face (i.e., $x = 0$) and at a low enough ac drive and light intensity (≈ 10 μW) to give results that were independent of drive and light intensity. It was also observed that the lifetime did not vary significantly over the scanning diameter until the light spot was within a few mm from the as-ground ingot surface and then decreased as that surface was approached. Independent measurements using the same ingot with a commercially available instrument that floods the whole specimen with infrared light and uses a 30-MHz operating frequency and capacitive coupling to sense the resulting conductivity changes gave a lifetime of about 7 ms. A possible explanation for the difference between this value and the presently obtained value of 4.8 ms is the non-negligible displacement current at 30 MHz in a 50,000 Ω•cm specimen (i.e., inequality 2 is not satisfied). The resulting effect of this added capacitive component of specimen impedance on this measurement is currently under investigation. Note, however, that this is not a problem at the 300-KHz operating frequency used with the present laser-scan technique.

Therefore, it has been demonstrated that this laser-scan technique can be used to profile an axially averaged low-level excess-carrier recombination lifetime over a scanning diameter to within a few diffusion lengths of the ingot surface. By rotating the specimen by 90 deg in figure 4 and renumbering the contacts accordingly, a second diameter, perpendicular to the first, can also be scanned without otherwise changing the system or specimen in any way. Only standard laboratory equipment (a low power He-Ne laser, a signal generator, and an oscilloscope) are needed and the procedure and data reduction are relatively simple and straightforward. This technique has the potential of providing a practical way to profile the radial variations of excess-carrier recombination lifetime in ingots of high-resistivity silicon. Axial profiling could, in principle, be done by using the techniques discussed in Section II above (e.g., by segmenting the four van der Pauw contacts), but this has not been explored.

One additional advantage of this technique is discussed in the following section where it is shown that this identical measurement can also produce a profile of the relative resistivity (i.e., $\rho(x)/\rho(o)$) over the scanned diameter. Since these two measurements use the same specimen and the same basic technique, all of the above discussion about ac drive, laser light intensity, validity of eq (4), etc. will also pertain to the following discussion of radial resistivity profiling.

IV. PROFILING RADIAL RESISTIVITY VARIATIONS

The technique for profiling excess-carrier recombination lifetime discussed in Section III above can also be used to profile radial variations of resistivity. The basic equation describing that lifetime measurement was eq (4). If this equation is solved for $\rho(x)$, one obtains:

$$\rho(x) = \frac{\pi L\ (-\Delta R)}{2b^2 \rho_{ave} (a^2 \Delta\sigma)} (b^4 + x^4) , \qquad (5)$$

where $\Delta R = \Delta V_{34}/I_{12}$. Consequently, at any given position of the laser beam (i.e., any given value of x), ΔV_{34} is a measure of $\rho(x)/(b^4 + x^4)$ if $\Delta\sigma$ could be made independent of x. If the on-time of the chopped laser beam T_{on} is short compared to the excess-carrier recombination lifetime in the silicon ingot, there will be negligible recombination during the interval that the laser is on, and $\Delta\sigma$ at the end of this interval will be given by:

$$\Delta\sigma = (\mu_+ + \mu_-)egT_{on} , \qquad (6)$$

where μ_+ and μ_- are the carrier mobilities, e is the electronic charge, and g is the photoexcitation rate of electrons and holes per unit volume. Clearly, g depends on the intensity of light in the laser beam, but it is virtually independent of all ingot-related variables such as dopant or deep-level density in the high-purity, detector-grade silicon of interest. Nothing in the above equation for $\Delta\sigma$ is a function of x, and $\Delta\sigma$ can be taken as a constant in eq (5) for any given experimental situation. If A is the amplitude of the change in the van der Pauw voltage at the end of the T_{on} period (see insert to fig. 5), then the relative resistivity at any position x is given by:

$$\frac{\rho(x)}{\rho(o)} = \frac{A(x)}{A(o)} \cdot \left(1 + \left(\frac{x}{b}\right)^4\right) , \qquad (7)$$

where A(x) and A(o) are the measured amplitudes at positions x and o, respectively.

In eq (6), it is assumed that the excess electron and hole densities at the end of the laser on-period were both equal to gT_{on}. Although excess electrons and holes will be generated equally for photoexcitation across the bandgap during the light-on period, it is possible for traps to capture one carrier preferentially and thus invalidate eq (6). This would have no adverse effects if that trap were uniformly distributed in the ingot specimen so that $\Delta\sigma$ would still be independent of x, but there are potential problems if the traps are inhomogeneously distributed and $\Delta\sigma$ varies with x. At the present time, the authors are unaware of any nondestructive measurement that can be made on these van der Pauw specimens to distinguish between inhomogeneous distributions of such traps and inhomogeneity of resistivity. Therefore, in any practical use of the laser-scan technique, it may be necessary to determine that the material in question has sufficiently low trap density or that the traps are sufficiently uniformly distributed to validate the assumption that $\Delta\sigma$ is independent of x.

This technique was tested on the 50,000 Ω·cm ingot specimen with removable silver-paste contacts that was used in the previous tests discussed above. The on-period of the laser beam was shortened from the 1-μs value of figure 5 to 0.4 μs, and amplitude A was measured at regular intervals along the scanning diameter. A value of $\rho(x)/\rho(o)$ was then calculated from eq (6) for each measurement position x. No significant variations of resistivity could be seen over the central 2/3 of the scanning diameter (i.e., $\rho(x)$ was constant to within about ±20 percent). It was concluded that the sensitivity of the system needed to be improved in order to measure accurately resistivity variations this small. However, $\rho(x)$ was observed to fall off to about 50 to

60 percent of its value at x = 0 near the ends of the scanning diameter. At the present time, there is no facility at the National Bureau of Standards for confirming these results. Therefore, plans are being made to develop a confirmation technique based on capacitive-voltage measurements of guarded Schottky barrier contacts spaced along the scanning diameter to measure the dopant density profile along the same diameter used in the laser-scan measurement. In addition, plans are being made to test this laser-scan technique with removable silver-paste contacts to an etched surface on the ingot specimen and with pressed-on capacitive contacts. It is felt that this additional work is necessary before this basic laser-scan technique can be recommended for routine use.

V. CONCLUSIONS

Three coupled techniques for nondestructively 1) measuring an average resistivity, 2) profiling the low-level excess-carrier lifetime, and 3) profiling the resistivity of cylindrical ingot specimens of high-resistivity detector-grade silicon have been proposed and are in the process of being evaluated. All three techniques treat the ingot section under test as a large van der Pauw specimen and require removable silver-paste contacts or pressed-on capacitive contacts. The profiling measurements require the use of ac current drive at a frequency low enough so that the displacement current is very much smaller than the charge current due to the extrinsic carriers. The profiling measurements use a highly penetrating 1.15-μm He-Ne laser beam as an optical probe to photoexcite excess carriers to modulate the local extrinsic conductivity for resistivity profiling and to allow observation of their decay for lifetime profiling. The conceptual and theoretical background for these measurements and the results of feasibility experiments obtained to date have been presented. These results show the expected behavior and produce reasonable results, but additional work is required to complete the feasibility experiments and to confirm the results on a few specimens by some independent technique.

VI. ACKNOWLEDGMENT

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Techniques for nondestructively characterizing the resistivity and excess-carrier recombination lifetime in ingots of high-resistivity, long-lifetime detector-grade silicon are being evaluated. In particular, three interrelated techniques for nondestructively: 1) measuring an average resistivity, 2) profiling the low-level excess-carrier lifetime, and 3) profiling the resistivity of cylindrical ingot specimens are proposed and are in the process of being evaluated. All three techniques treat the ingot under test as a large van der Pauw specimen and require removable silver-paste contacts or pressed-on capacitive contacts. The profiling measurements utilize a highly penetrating 1.15 μm He-Ne laser beam as an optical probe. The conceptual and theoretical background for these measurements and the results of feasibility experiments obtained to date are presented. These results show the expected behavior and produce reasonable results, but additional work is required to complete the feasibility experiments and to confirm the results on a few specimens by some independent technique.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

detector-grade silicon; lifetime profiling; resistivity profiling; van der Pauw measurements

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