Spreading resistance method
-Performance and experimental errors-
-Technical note-

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Abstract

The electrical performances of silicon-based integrated circuits are closely coupled to the details of dopant depth distribution in silicon. One of the most used experimental technique which yield the depth distribution of the electrically active dopants in silicon is the spreading resistance (SPR) method. A description of the SPR method and the experimental errors which can be introduced by this method in the characterization of boron diffused layers in silicon are presented in this paper.

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Keywords: Silicon, depth profiling

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The electrical performances of silicon-based integrated circuits are closely coupled to the details of dopant depth distribution in silicon. One of the most used experimental technique which yield the depth distribution of the electrically active dopants in silicon is the spreading resistance (SPR) method. A description of the SPR method and the experimental errors which can be introduced by this method in the characterization of boron diffused layers in silicon are presented in this paper.

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1. INTRODUCTION

Solid state diffusion and ion implantation are two doping technique widely used in the fabrication of silicon-based integrated circuit’s (IC’s). Since the details of the impurity distribution obtained during these processing steps are closely coupled to the electrical performances of IC’s, some techniques have been developed for the characterization of electrically active dopant profiles in silicon. Two of the most commonly experimental techniques which yield the distribution of the electrically active centers in silicon are: the capacity-voltage (C-V) technique and the spreading resistance (SPR) technique.

The C-V technique offers a simple, fast, non-destructive method used to obtain the profile of majority carriers, but only when the small junction depths can be measured (a profiling depth from 0.1µm to an upper limit (norm. 0.6µm) which depend on substrate and total implant dose). Moreover, there are also two requirements on samples characterized by this method: (i) the doped layer must be obtained by a low-dose implant ($\leq 10^{14}$ion/cm²) and (ii) the conductivity type of the dopant must be the same with the conductivity type of the substrate. The detectable limit of carrier concentration given by the C-V method is about $10^{16}$cm⁻³.

The SPR method is a powerful technique due to the possibility of measuring arbitrary profiles (layers with different conductivity types) with no restriction as to the doping level. The lowest limit of profiling depth is ~0.1µm and there is not an upper limit of junction depths measured by this method. The detectable limit of carrier concentration given by the SPR method is about $10^{15}$cm⁻³.

Because of the wide capabilities of the SPR method (no restriction on the doping level and on the type of dopants), this technique is frequently used for electrical characterization of diffused and implanted layers in silicon (see, for example, Ref. 1-5).

As for any experimental technique, also for SPR technique, one of the most important problems is the accuracy of the method. The aim of this paper is to present the experimental errors which can be introduced by SPR method in the characterization of electrically active dopant depth profiles in silicon. For a better understanding of this subject, a detailed description of the SPR method has been shown in Sec. 2. The experimental errors obtained in the characterization of boron diffused layers in n-type silicon wafers by SPR method are presented in Sec. 3 and the concluding remarks are summarized in Sec. 4.

2. THE SPREADING RESISTANCE METHOD

Spreading resistance method was used to measure automatically the electrically active dopant profiles in silicon crystals. In this method, the sample which has to be measured is waxed onto a bevel block and is glided over a plate containing a polishing compound. Blocks with different bevel angles, from 17° to 11°32’, are usually available and are chosen to provide a desired depth resolution profiling.
After the polishing action of the sample, the bevel sample block is placed on a X-Y stage, which will move automatically in steps ranging from 0.25μm to 250μm. Two probes are positioned above the flat surface and are lowered until they make contact with the surface. A small voltage is applied between the two probes and a spreading resistance is measured. The two probes are then lifted, the stage moves over an adjusted step Δx and the action is repeated until the completely spreading resistance profile is obtained. The spreading resistance data are then corrected and converted into the corresponding resistivity values using adequate formulas (see section 2.3). The final values for resistivity are then converted into the corresponding carrier concentration profile through the use of the Irvin's curve [8].

Details regarding sample preparation, the measurement of the spreading resistance profile and the correction and conversion into the corresponding carrier concentration profile are presented in sec 2.1+2.3.

2.1 Sample preparation

For characterization of doping depth profiles in silicon by spreading resistance method, a special procedure for preparing the samples is recommended. In this process, a test chip of 1-2mm width and 2-3mm length is taken from a wafer which has to be profiled and is waxed onto a bevel block as is shown in Fig 1a. The mounted sample is attached to ground face of a piston which is then inserted in a well fitting cylinder. This assembly [Fig 1b] will then be glided over a plexiglas surface which contains the polishing compound. The polishing compound can be chemical in its action or rather mechanical. The later type is superior to the first one [6] and among these compounds a very fine diamond particle paste called METAD1 gives the best results [6]. The grinding is done in one direction only, with the abrasive action perpendicular to and toward the bevel edge. Fig 1c shows the system after the polishing action is completed.

2.2 The spreading resistance measurement

The lapping block can then be removed from the piston and the measurement of the spreading resistances can be done on the sample which remains attached to the block, Fig 2.

The bevel sample block is placed on a X-Y stage, which will move automatically in steps to the right in Fig 2. The sample is positioned in such a way that the bevel edge of the sample is perpendicular to the stepping direction.

Two probes with tips from an osmium-tungsten alloy and a tip radius of typically 20μm, mounted on a gravity-loaded probe arm assembly, are positioned above the flat surface. The probe spacing w can be varied and is usually in the range of 20±100μm. The probe are lowered until they make contact with the surface and a pressure given by 5, 10, 20 or 45mg probe loading will be applied. The diameter of the contact is about 4-6μm.

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Fig. 1 Schematic presentation of the three stages for obtaining a beveled sample to be used in spreading resistance measurements.

a) The sample is mounted on the lapping block which shows an angle θ;
b) The lapping block is fastened to a piston and introduced into a cylinder. This assembly will glide over a plate containing the polishing compound;
c) After the polishing action the sample, still attached to the lapping block, shows a polished bevel.
lapping block

direction of motion of the block

Fig. 2 Schematic presentation of the measurement procedure in the spreading resistance technique. The two probes, a distance \( x \) apart, are lifted while the block moves to the right over a distance \( \Delta x \). The probes are then lowered until contact is made with the lapped bevel. While starting, with the probes aligned parallel to the bevel edge, the block motion is perpendicular to this edge.

A small voltage \( \Delta V \) is applied between the two probes and the spreading resistance given by

\[
R_s = \frac{\Delta V}{I}
\]

is measured. The two probes are then lifted, the stage moves over an adjusted distance \( \Delta x \) and the action is repeated until completion.

The spatial resolution required for a given profile can be determined if the exact bevel angle and the horizontal stepping increment (Fig. 2) are known. From the Fig. 2, it is obvious that:

\[
\Delta y = \Delta x \sin \theta
\]

where \( \Delta y \) - the spatial depth resolution (vertical step) during spreading resistance runs, \( \Delta x \) - the horizontal step along the bevel surface, \( \theta \) - the bevel angle.

The vertical column on the left of the Table 1 lists the horizontal step increments available on the mechanical subsystem of a usual spreading resistance system. The standard bevel angles are also displayed across the top of the Table 1. Below these, are the values of the sine of the angle. The remaining figures are values of \( \Delta y \), the incremental depth in either micrometers or Angstroms units, as indicated.

Table 1: The values of incremental depth for the horizontal step increment and standard bevel angles available on the mechanical subsystem of an usual spreading resistance system.

<table>
<thead>
<tr>
<th>Bevel Angle, ( \theta )</th>
<th>17° 12</th>
<th>5° 48</th>
<th>2° 32</th>
<th>1° 0° 14</th>
<th>0° 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta y ) (nm)</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

An example of a spreading resistance data for boron diffusion in a 10Ω cm \(<111>\) n-type silicon substrate is given in Fig. 3. The test chip was measured for a bevel angle of 0° 34° and an horizontal step increment of 2.5 μm.
providing that the assumption used in the derivation of the equation hold, i.e.: i) the distance to any boundary surface of the sample from either contact is $>>a$, ii) the resistivity $\rho$ is homogeneous throughout the sample, iii) there are not surface films or potential barriers at the contacts.

In practical spreading resistance measurements on many of thin-layer structures of current interest in semiconductor technology (e.g. epitaxial, diffused or ion-implanted layers) the assumptions behind simple equation (3) are often violated. First of all, the structure is not planar anymore, but because of the small angles used it is justified to treat it as planar. The spreading resistance of an homogeneous layer of finite thickness is strongly modified, dependent on the type of the boundary layer. This is shown in Fig. 4, where three possible cases are considered [7]. Fig 4a shows the semi-infinite substrate for which the Eq.(3) holds. For a conducting boundary (e.g. low-high epitaxial interfaces) as is shown in Fig.4b, the potential drop in the lateral direction will be smaller than for Fig 4a resulting in a smaller resistance value ($R_c<p/2a$). For an insulating boundary (e.g. low-lackage p-n junctions or silicon insulator interfaces) however the current is forced into the lateral direction increasing the voltage drop along the surface and resulting in a higher spreading resistance value ($R_i<p/2a$) (Fig.4c).

The effect of such boundaries is accounted by calculating the appropriate correction factors for each point of the spreading resistance profile. The measured spreading resistance can be given by:

$$R_s = \frac{\rho}{2a} \cdot CF$$

in which $CF$ is the “Dickey” correction factor, dependent on the spacing between the two spreading resistance contact, on the radius contact and on the distance from the probe surface to the conduction or insulating boundary.

![Fig. 4 Echipotential (dashed) and field (full) lines for an ideal probe contact on three different geometries [6].](image-url)
The Dickey correction factors are calculated from a combination of an approximate line analog, assuming a single-layer structure of uniform resistivity, backed by either a perfectly insulating boundary or by a perfectly conducting boundary.

For insulating boundary distances equal or greater than "a", the correction factor formula applicable is:

\[
C' = 1 - \frac{2a}{m} \cdot \frac{t}{w} \left[ \frac{2t}{w} + 2 \ln \left( \frac{w}{2t} \right) \right] - 0.2318
\]

(5)

where "w" is the spacing between the two spreading resistance contacts and "t" is the distance from the probe surface to the insulating boundary.

For insulating boundary distances less than "a", the correction factor is given by:

\[
C' = \frac{2a}{m} \ln \left( \frac{w}{t} \right)
\]

(6)

Conducting boundary correction factors are generated for t>1.33a by the relation:

\[
C' = 1 - \frac{2a}{m} \cdot \frac{t}{w} \left[ M\left( \frac{w}{4t} \right) - M\left( \frac{w}{2t} \right) \right]
\]

(7)

where \(M(\lambda) = 1/\lambda - 2 \ln \lambda - 0.2318\)

and by the relation

\[
C' = \frac{4t}{m} \left[ 1 + \left( \frac{2t}{m} \right) \ln 2 \right]
\]

(8)

for t<1.33a.

The Dickey correction factors defined by equations (6) to (8) give good results whenever the layer being processed is essentially uniform in resistivity (such as a well controlled epitaxial layer). However, for structures with significant resistivity variation perpendicular to the probed surface (such as a thin diffused layer), the unmodified Dickey correction described above can produce errors in the derived carrier concentration as large as an order of magnitude.

To provide for inhomogeneous resistivity cases, it is need to determine an "effective thickness" for each point on a spreading resistance profile. The "effective thickness" may be thought of as the distance from a given point on the profile to a "floating" boundary below the probes.

For the "insulating boundary" case, the effective thickness is taken as the depth below a particular point in the carrier concentration profile of the structure where the carrier concentration has fallen off by 1/e, where "e" is the Euler's number 2.718281828.

The "effective thickness" for the "conducting boundary" case is taken as that distance below a point on the carrier concentration profile where the carrier concentration increases by a factor of "e".

In order to apply these "e-factor" corrections, the effective thickness values for each point of the measured profile must be obtained from a first approximation to the carrier concentration profile, which is determined either by: 1) converting the measured spreading resistance values to resistivity and to carrier concentration through the appropriate spreading resistance calibration curve or 2) by the making use of an appropriate correction procedure such as the unmodified Dickey correction factor which assumes the layer to be of homogeneous resistivity from the point in question down to the underlying boundary.

In either case, once the effective thickness values are determined, it is need to return to the raw spreading resistance profile and calculate and apply the appropriate Dickey correction for each point, using the effective thickness value determined for that point.

The final value for \(p\) is then converted to net carrier concentration through the use of the Irvin's curve [8], which is a compilation of a great amount of the experimental data. The resulting carrier concentration profile is assumed to be the "true" profile for the layer.

The corresponding profile for the boron diffusion in the 10Ω cm <111> n-type substrate at T=925°C, for which the spreading resistance values are shown in Fig 3, is shown in Fig 5.

![Fig. 5](image-url)
3. The experimental errors

As we told in introduction, one of the most important problems for any experimental technique, and also for the SPR method is the accuracy of the method.

The accuracy of each point in a SPR profile is given by the accuracy in depth and carrier concentration measurements. The accuracy in depth measurement depends on the accurate knowledge of the bevel angle \( \theta \), an accurate definition of the bevel edge and an accurately setting of the horizontal step increment \( \Delta x \). The accuracy in carrier concentration measurement depends on the reproducibility of the measured spreading resistance \( R_s \), the accuracy of the \( p-R_s \) calibration and the accuracy of the CF calculations.

Because there is not a simple way of judging the accuracy of depth and carrier concentration measurement in a SPR profile, we chosen an experimental way to check the magnitude of errors introduced by this method.

The spreading resistance probe system used in this work is the model SSM-130 built by Solid State Measurements, Inc. The probes are made of an osmium-tungsten alloy and the pressure of probe loading is applied by 20mg weights. The sample is placed on a X-Y stage and the X drive is automatically stepped after each measurement. Two horizontal steps of about 5\( \mu \)m and respectively 2.5\( \mu \)m have been used in this experiment. The probe spacing of the SSM-130 probe system is 100\( \mu \)m and the contact radius of the same system is approximately 3\( \mu \)m.

\(<111>\)-oriented n-type silicon wafers, with a resistivity of 10\( \Omega \)cm have been thermal diffused with boron using a BN solid source. A small sample, with an area of approximately 5x10mm\(^2\), has been cut from the middle of the wafer and used for SPR measurements. In this way, we have assumed that the errors obtained in SPR measurements performed on this sample are given only by the SPR method and not by the inhomogeneous doping through the wafer. This sample has been divided in eight test chips and each test chip has been angle lapped with a slurry of a 0.25\( \mu \)m diamond abrasive and oil on a frosted glass plate using a bevel block of 34'.

The SPR profiles of boron in diffused layer are shown in Fig. 6. Fig 6a) shows the SPR profiles performed for an horizontal step increment of 5\( \mu \)m. Fig 6b) shows the SPR performed on the same test chips as in Fig 6a), but for an horizontal step increment of 2.5\( \mu \)m.

![Graph showing SPR profiles](image-url)
The most important parameters extract from an SPR profile are the junction depth, the integral number of dopants per unit area of diffused layer and the surface carrier concentration.

The accuracy of junction depth measurement obtained for a horizontal step increment of 5μm is of the order of ±0.026μm. This accuracy can be improved if a smaller horizontal step is used. For example, the accuracy of junction depth became of the order of ±0.013μm when the horizontal step increment has been decreased to 2.5μm. This result is very well observed in Fig 7, where the standard deviation (represented as error bars) of junction depth measurements corresponding to the SPR profiles presented in Fig 6a is twice times bigger than the standard deviation of junction depth measurements corresponding to the SPR profiles presented in Fig 6b.

The accuracy of measurements of integral number of carriers/unit area obtained for a horizontal step increment of 5μm is of the order of 3.3%. If the horizontal step increment has been decreased to 2.5μm a smaller accuracy has been obtained (±4.2%). Fig 8 shows the integral number of carriers/unit area corresponding to the SPR profiles presented in Fig 6a and Fig 6b. As can be seen from this figure a systematic error is introduce by SPR method in the measurement of integral number of carriers/unit area for different horizontal steps. The Fig 8 shows also that the standard deviation of total number of carriers/unit area (represented as error bars) corresponding to the SPR measurements performed at Δx=2.5μm is bigger than the standard deviation corresponding to the SPR measurements performed at Δx=5μm.

The accuracy of surface carrier concentration measurements obtained for an horizontal step increment of 5μm is of the order of 27%. If the horizontal step increment has been decreased to 2.5μm a smaller accuracy has been obtained (±43%). This result is observed also in Fig 9 where the values of surface carrier concentration corresponding to the SPR profiles showed in Fig 6a and Fig 6b and their standard deviation are presented.

Fig. 7 The values of junction depth and their standard deviations (represented as error bars) corresponding to the SPR profiles presented in Figs 6a and 6b.

Fig. 8 The values of total number of carriers/unit area and their standard deviation (represented as error bars) corresponding to the SPR profiles presented in Fig 6a and Fig 6b.

Fig. 9 The values of surface carrier concentration and their standard deviation (represented as error bars) corresponding to the SPR profiles presented in Fig 6a and Fig 6b.
4. CONCLUSIONS

In summary, we have experimentally demonstrated that SPR method used for characterization of electrically profiles in silicon has an accuracy of junction depth measurement of the order of ±0.026μm for an horizontal step increment of 5μm. This accuracy is improved to a value of about ±0.013μm if the horizontal step distance is decreased to 2.5μm. Instead of this result, the best accuracy of measurements for integral number of carriers/unit area and surface carrier concentration is obtained for the case of SPR measurements performed at horizontal step increment of 5μm (±3.3% and respectively ±2.7%).

5. REFERENCES