

TITLE OF THE INVENTION
METHOD AND APPARATUS FOR MEASURING QUANTITATIVE
VOLTAGE CONTRAST

Field of the Invention

The present invention relates to a method and apparatus for making, and more specifically for correcting, quantitative voltage contrast measurements (QVCM).

5 Background of Invention

There are known various conventional quantitative voltage contrast measurement systems for scanning electron microscopes and electron beam testing, such as that described in "An Analysis of the Local Field
10 Effect Probe Voltage Measurements", Nakamura et al., 1993, Scanning Electron Microscopy, Pages 1187-1195; "VLSI Testing Using the Electron Probe", H. P. Feuerbaum, Scanning Electron Microscopy, 1979, pages 285-296; and "Local Field Effects on Voltage
15 Measurement Using a Retarding Field Analyser in the Scanning Electron Microscopy", Fujioka et al., Scanning Electron Microscopy, 1981, pages 323-332, which use feedback techniques. There are other known systems such as that described in "The effect of passivation
20 on the observation of voltage contrast in the scanning electron microscope", D. M. Taylor, The Institute of Physics, Vol. 11, 1978, pages 2443-2454; and "A voltage contrast detector for the SEM", Hardy et al., Journal of Physics E: Scientific Instruments, Vol. 8, March 10,
25 1975, pages 789-793, which use the peak detection method. These known systems suffer from poor accuracy due to various error components like the potential barrier effect, off-normal incidence injection of

secondary electrons into the analyzing field, lens effect, and analyzer geometry effects. These systems require a high extraction field (500 V/nm to 1000 V/nm) to minimize the error components due to local field
5 effects (both Types I and II) acting on secondary electron trajectories. Unfortunately, the use of these high extraction fields is not compatible with certain sensitive specimens or with passivated specimens.

Furthermore, conventional systems cannot perform
10 accurate voltage measurements on underlying structures in multi-level component systems due to errors from charging effects (e.g., in a multi-level component system where underlying metal structure may be exposed by focused ion beam milling with walls of insulator
15 material surrounding the point of measurement).

SUMMARY OF THE INVENTION

An object of the present invention is to provide a method and apparatus for making quantitative voltage contrast measurements which overcomes the drawbacks of
20 the conventional systems described above.

A further object of the present invention is to provide a method and apparatus for making quantitative voltage contrast measurements which use low extraction voltages and correct for errors due to local field
25 effects (both Types I and II).

Another object of the present invention is to provide a method and apparatus for making quantitative voltage contrast measurements which correct for charging due to a contaminant layer forming as a result
30 of a specimens exposure to air or under electron beam bombardment.

Another object of the present invention is to provide a method and apparatus for making quantitative voltage contrast measurements which perform accurate
35 voltage measurements on underlying structures in a multi-level component system.

Another object of the present invention is to provide a lock-in-peak-detection quantitative voltage contrast measurement setup.

These and other related objectives are achieved by
5 providing a method of measuring quantitative voltage contrast comprising the steps of: (a) outputting instructions from a processor to an energy analyzer and scanning electron microscope; (b) locating an electron beam of said scanning electron microscope on a specimen
10 electrode of a specimen structure based on said instructions; (c) varying a grid voltage of said energy analyzer in accordance with said instructions; (d) detecting secondary electron emission from said specimen electrode with a detector of said scanning
15 electron microscope; (e) determining a measured peak voltage of said specimen electrode based on output from said detector; (f) obtaining a specimen electrode voltage corrected for type I local field effect error using said measured peak voltage and a type I
20 calibration curve, said type I calibration curve representing peak voltage versus specimen electrode voltage; and (g) correcting for type II local field effect error in the output of said step (f) based on a type II calibration curve, said type II calibration
25 curve representing a shift in specimen electrode peak voltage versus adjacent electrode voltage.

The objectives of the present invention are also achieved by providing an apparatus for measuring quantitative voltage contrast comprising: means for
30 outputting instructions to an energy analyzer and scanning electron microscope; means for locating an electron beam of said scanning electron microscope on a specimen electrode of a specimen structure based on said instructions; means for varying a grid voltage of
35 said energy analyzer in accordance with said instructions; means for detecting secondary electron emission from said specimen electrode; means for

determining a measured peak voltage of said specimen electrode based on output from said means for detecting; means for obtaining a specimen electrode voltage corrected for type I local field effect error
5 using said measured peak voltage and a type I calibration curve, said type I calibration curve representing peak voltage versus specimen electrode voltage; and means for correcting for type II local field effect error in output of said means for
10 obtaining based on a type II calibration curve, said type II calibration curve representing a shift in specimen electrode peak voltage versus adjacent electrode voltage.

These and other related objectives of the present
15 invention will become more readily apparent from the detailed description given hereafter. It should, however, be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of
20 illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

25 The present invention will become more fully understood from the detailed description here-in-below and the accompanying drawings which are given by way of illustration only, and thus do not limit the present invention.

30 Figures 1-4(c) are flow charts illustrative of the method according to the present invention;

Figure 5 is a block diagram of the measurement apparatus according to the present invention;

35 Figure 6 is a schematic diagram of the energy analyzer according to the present invention;

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Figure 7 is an example of a Type I calibration curve;

Figure 8 is an example of a Type II calibration curve;

5 Figure 9 is a graph of the error in the measured specimen electrode voltage versus the actual specimen electrode voltage; and

10 Figure 10 is a scatter plot of the error on the electrode voltage versus the actual voltage for specimen and adjacent electrodes.

The above-mentioned drawings will be described in detail in the following detailed description wherein like reference numerals identify like elements.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

15 Figure 5 illustrates an embodiment of a measurement apparatus of the present invention. In Figure 5, reference numeral 10, represents a personal computer (PC) or equivalent thereto, reference numeral 12 represents a buffer/amplifier circuit, reference
20 numeral 14 represents a scanning electron microscope (SEM), reference numeral 16 represents an energy analyzer, reference number 18 represents a detector, reference numeral 20 represents a lock-in amplifier, reference numeral 22 represents an oscilloscope, and
25 reference numeral 24 represents a function generator.

The buffer/amplifier circuit 12 is connected to the PC 10, the energy analyzer 16, and the function generator 24. The function generator 24 is also connected to the lock-in amplifier 20. The lock-in
30 amplifier 20 is further connected to the PC 10 and detector 18. In Figure 5, the lock-in amplifier is shown connected to oscilloscope 22; however, this connection is optional.

The SEM 14 operates cooperatively with energy
35 analyzer 16 and detector 18 under the control of PC 10 or a skilled operator. Specifically the PC 10 or the

operator would control an X-Y table holding a specimen stage. The energy analyzer (or spectrometer) 16 used in the measurement apparatus can be a planar retarding field spectrometer, a hemispherical retarding field spectrometer, a collimating magnetic field spectrometer, or any commercially available spectrometer for voltage contrast measurements/electron beam testing.

A schematic diagram of the planar retarding field analyzer 16 used in the measurement apparatus of Figure 5 is illustrated in Figure 6. The energy analyzer 16 includes a reflection grid having a reflection grid voltage V_{RE} , a retarding grid having a retarding grid voltage V_R , a shielding grid having a shielding grid voltage $V_{SH} = V_R$, and an extraction grid having an extraction grid voltage V_E . Each of the above described grids are arranged parallel to one another and to a specimen plane, and are separated by predetermined distances. In the embodiment of the energy analyzer 16 shown in Figure 6, the reflection grid is separated from the retarding grid by 7.5mm, the retarding grid is separated from the shielding grid by 10.25mm, the shielding grid is separated from the extraction grid by 10.25mm, and the extraction grid is separated from the specimen plane by 2mm. The specimen plane includes a specimen having a specimen electrode and adjacent electrodes.

Figure 6 also shows that the grids have a width of 29.5mm. For purposes of illustration, an electron beam represented by a dash-dot line is shown incident on specimen electrode V_s . The resulting secondary electrons are represented by a vector having an angle α with respect to the specimen plane and an angle θ with respect to the electron beam. Also shown in Figure 6, the specimen and adjacent electrodes have a width of dimension a and are spaced apart by a distance

b. The values of width a and space b will depend on the specimen being tested.

The PC 10 can be an IBM personal computer or other processing device which includes an analog-to-digital converter and a digital-to-analog converter for interfacing with the measurement apparatus. The buffer/amplifier circuit 12 receives instructions from the PC 10, and outputs the reflection grid, retarding grid, and shielding grid voltages V_{RE} , V_R , V_{SH} to the energy analyzer 16 in accordance with the received instructions. The extraction grid voltage V_E is tapped from the voltage supply for detector 2. In the embodiment shown in Figure 6, during operation, the reflection grid voltage V_{RE} is set to $-5V$, the extraction grid voltage V_E is set to $100V$, and the retarding grid voltage V_R , and thus the shielding grid voltage V_{SH} , are varied. Varying of the retarding grid voltage V_R is discussed in detail below.

The buffer/amplifier circuit 12 also outputs voltages V_s , V_1 , and V_2 to apply to the specimen and adjacent electrodes in accordance with the received instructions. The buffer/amplifier circuit 12 also receives, from the function generator 24, a small a.c. signal of about $400mV$ peak-to-peak. The buffer/amplifier circuit 12 combines, in a summing circuit (not shown), the small a.c. signal with the d.c. retarding grid voltage generated in accordance with the instructions from the PC 10. The buffer/amplifier circuit 12 supplies the resulting signal to the energy analyzer 16 for biasing the retarding grid.

During operation, the SEM 14 directs an electron beam on the specimen electrode, and the detector 18, which can be a scintillator-photomultiplier detector or any other type of secondary electron (SE) detector, detects secondary electron emissions (See Fig. 6) from the specimen electrode. The detector 18 outputs to the

lock-in amplifier 20 a voltage representing the detected secondary electrons. The lock-in amplifier 20 also receives the small a.c. signal from the function generator 24 as a reference signal. The lock-in
5 amplifier 20 differentiates the curve representing the output of detector 18 versus the retarding grid voltage V_r . The output of the lock-in amplifier 20 corresponds to the energy distribution of secondary electron emissions. The shift in the peak of the secondary
10 electron energy distribution provides information on the voltage of the electrodes. The retarding grid voltage V_r where the output of the lock-in amplifier 20 is maximum indicates the peak of the secondary electron distribution. The lock-in amplifier 20 may be a
15 commercially available lock-in amplifier such as the SR-530 Lock-in Amplifier from Stanford Research Systems.

The PC 10 receives the output of the lock-in amplifier 20, and measures the quantitative voltage
20 contrast based thereon. The output of the lock-in amplifier 20 can also be monitored using oscilloscope 22.

The quantitative voltage contrast measurement performed by the measurement apparatus of Figure 5 will
25 now be described with reference to the flow charts of Figures 1-4(c).

The flow chart of Figure 1 shows the method for making quantitative voltage contrast measurements. In step S2 a Type I calibration curve is obtained. The
30 Type I calibration curve, which is a plot of peak voltage versus specimen electrode voltage, will be used in later steps for correcting Type I local field effect errors.

Figure 2 is a flow chart showing the method for
35 obtaining the Type I calibration curve. The description of the flow chart shown in Figure 2 will be made in association with an example of a Type I



calibration curve shown in Figure 7. A three-electrode, unpassivated reference structure having approximately similar electrode width:spacing as the actual specimen structure, such as shown in Figure 6, is placed in the energy analyzer 16. In obtaining the curve of Figure 7, an unpassivated reference structure having an electrode width:spacing of 10:5 microns was used. The specimen electrode voltage V_s is fixed, and the adjacent electrode voltages V_1 and V_2 are set to zero in step S20. In Figure 7, the specimen electrode voltage V_s was initially set to -8V.

The retarding grid voltage is then varied in step S22. In obtaining the calibration curve of Figure 7, the retarding grid voltage V_R was varied from 5V to -20V in increments of 0.5V. A finer increment could be used depending on the resolution and accuracy required for the measurement. The PC 10 then stores in step S24 the value of V_R , when the output of the lock-in amplifier 20 is a maximum, along with the corresponding value of V_s . The stored value of the retarding grid voltage V_R is the peak voltage at the specimen electrode voltage V_s .

The above steps S20-24 obtain one point on the Type I calibration curve. To obtain successive points, the above operations are repeated for different values of the specimen electrode voltage V_s . For instance, as shown in Figure 7, the specimen electrode voltage was varied from -8V to 8V in increments of 1.0V. Again, finer increments could be chosen depending on the desired accuracy and resolution. Thus, in step S26, it is determined whether the Type I calibration curve is completed (i.e., whether $V_s = 8V$ for the example shown in Figure 7). If, in step S26 it is determined that the Type I calibration curve is not completed, then in step S28, the value of the specimen voltage V_s is changed according to the increments discussed above, and steps S20-24 are repeated.

If, in step S26 it is determined that the Type I calibration curve is completed, then step S2 is complete, or, as an option, in step S30 the PC 10 can plot the Type I calibration curve prior to the completion of step S2. For instance, the PC 10 could display on a display screen or output to a printer, the Type I calibration curve such as shown in Figure 7. Figure 7 further illustrates that the method of obtaining the Type I calibration curve can be repeated for the same reference structure to obtain a repeated Type I calibration curve. The repeated Type I calibration curve represents the shift in the repeated measurement from the original measurement due to positive charging of a contaminant layer which builds up on the surface of a structure (reference or specimen) as a result of prolonged electron beam bombardment and exposure to air.

As shown in Figure 1, after obtaining the Type I calibration curve, the Type II calibration curve is obtained in step S4. The Type II calibration curve, which is a plot of the shifts in peak voltage of the specimen electrode versus adjacent electrode voltages, will be used in later steps to correct for Type II local field effects.

Figure 3 is a flow chart showing the method for obtaining the Type II calibration curve. The description of the flow chart shown in Figure 3 will be made in association with an example of a Type II calibration curve shown in Figure 8. A three-electrode, unpassivated reference structure having approximately similar electrode width:spacing as the actual specimen structure, such as shown in Figure 6, is placed in the energy analyzer 16. In obtaining the curve of Figure 8, an unpassivated reference structure having an electrode width:spacing of 10:5 microns was used. One of the adjacent electrode voltages V_1 and V_2 is fixed, and the other adjacent electrode voltage and

the specimen electrode voltage V_s are set to zero in step S32. For purposes of description, it will be assumed that adjacent electrode voltage V_2 is fixed. As shown in Figure 8, the adjacent electrode voltage V_2 is initially fixed at -8V. The retarding grid voltage V_R is then varied in step S34.

The maximum range of variation for the retarding grid voltage is 5 to -50V in increments of 1V. Typically, however, the range of 5 to -20V at 0.5V increments is used. As discussed above, the size of the increment can be changed to suit accuracy requirements. The range itself must simply be sufficient to obtain the peak of the secondary electron distribution. The above equally applies to obtaining the Type I calibration curve.

The PC 10 then stores in step S36 the value of V_R , when the output of the lock-in amplifier 20 is a maximum, as a measured voltage and stores the corresponding value of V_2 . The PC 10 then determines the shift in the retarding grid voltage. This is accomplished by temporarily setting the adjacent electrode voltage to a base level, e.g. zero, and storing the output of the lock-in amplifier as a reference voltage. Afterwards, the adjacent electrode voltage V_2 is returned to its previous voltage level. The PC 10 then determines the shift in retarding grid voltage V_R by subtracting the reference voltage from the measured voltage.

The above steps S32-36 obtain one point on the Type II calibration curve. To obtain successive points, the above operations are repeated for different values of the adjacent electrode voltage V_2 . For instance, as shown in Figure 8, the adjacent electrode voltage V_2 was varied from -8V to 8V in increments of 1.0V. Thus, in step S38, it is determined whether the Type II calibration curve is completed (i.e., whether $V_2 = 8V$ for the example shown in Figure 8). If, in step S38 it

is determined that the Type II calibration curve is not completed, then in step S39, the value of adjacent electrode voltage V_2 is changed according to the increments discussed above, and steps S32-S36 are
5 repeated.

If, in step S38 it is determined that the Type II calibration curve is completed, then step S4 is complete, or, as an option, in step S40 the PC 10 can plot the Type II calibration curve prior to the
10 completion of step S4. For instance, the PC 10 could display on a display screen or output to a printer, the Type II calibration curve as shown in Figure 8.

After obtaining the Type II calibration curve, an actual specimen structure is located within the energy
15 analyzer 16, and quantitative voltage contrast measurements, corrected for Type I local field effects, are made for N electrodes of the actual specimen structure. The number of electrodes to be measured, N, varies depending on the specimen, and each of the N
20 electrodes are treated in turn as the specimen electrode.

The SEM 14 locates the electron beam on a specimen electrode in step S6. Then in step S8, the retarding grid voltage V_R is varied such as was described in
25 obtaining the Type I and II calibration curves, the output of the lock-in amplifier 20 is monitored, and the PC 10 determines the measured peak voltage of the specimen electrode as the retarding grid voltage V_R corresponding to the maximum output of the lock-in
30 amplifier S20.

Next, in step S10, the PC 10 obtains a quantitative voltage contrast measurement of the specimen electrode corrected for Type I local field effects by reading, from the stored Type I calibration
35 curve (see Figure 7), the specimen electrode voltage corresponding to the measured peak voltage. If a peak voltage of the Type I calibration curve does not match

the measured peak voltage, then the PC 10 interpolates the specimen electrode voltage based on the Type I calibration curve values greater than and less than the measured peak voltage. While the embodiment described
5 herein uses linear interpolation, applicants contemplate the use of non-linear interpolation techniques. Alternatively, curve fitting techniques could be used. The above comments apply equally to all interpolation performed by the present invention, and,
10 therefore, will not be repeated.

The PC 10 further monitors the period of time the actual specimen structure undergoes electron beam bombardment and exposure to air. When the period of time exceeds a predetermined threshold, the PC 10
15 determines whether there is a positive charging present, due to the buildup of a contaminant layer on the specimen surface, by repeating the Type I calibration curve measurement and noting any significant shifts in the repeated calibration curve
20 from the original calibration curve. Accordingly, in determining the measured peak voltage for the remaining electrodes of the actual specimen structure, the PC 10 uses the repeated Type I calibration curve in the same manner as the Type I calibration curve.

25 The number of electrodes N depends on the actual specimen structure, and in step S12, it is determined whether all N electrodes have undergone the measurements of steps S8 and S10. If the answer in step S12 is no, then in step S14, the SEM 14 locates the
30 electron beam on the next electrode to be measured as the specimen electrode. Steps S8 and S10 are then repeated for the new specimen electrode.

If the answer in step S12 is yes, then in step S16, PC 10 corrects for the Type II local field effect
35 on the quantitative voltage contrast measurements. Figures 4(a)-4(c) are flow charts showing in greater detail the steps comprising step S16. The correction

scheme for Type II local field effects, elaborated in the flow chart of Figures 4(a)-4(c), includes two iterative processes.

In the first iterative process, the voltages of
5 the adjacent electrodes for each of the N electrodes
are examined, and the shift in the peak voltage due to
the voltages of the adjacent electrodes are determined
for each of the N electrodes using the Type II
calibration curve. The PC 10 then determines a
10 corrected peak voltage for each of the N electrodes
using the determined shifts in the peak voltage, and
determines the actual N specimen electrode voltages
therefrom. If the largest peak voltage correction
amount falls below a predetermined tolerance (i.e.
15 achieves a desired measurement accuracy), then the
quantitative voltage contrast measurement process ends;
otherwise, the PC 10 begins a second iterative process.

The second iterative process differs from the
first iterative process in that the peak voltage
20 correction amounts of the adjacent electrodes are used,
instead of the voltages of the adjacent electrodes, to
determine the shifts in the peak voltage for each of
the N electrodes. The remainder of the quantitative
voltage contrast measurement process continues as in
25 the first iterative process. If, however, the largest
peak voltage correction amount of the second iterative
process exceeds the predetermined tolerance, the second
iterative process is repeated, and will only terminate
upon reaching the desired measurement accuracy. Each
30 successive iteration of the second iterative process
uses the peak voltage correction amounts of the
previous iteration of the second iterative process.

The first and second iterative process will now be
described in detail with respect to Figures 4(a)-4(c).
35 At the beginning of step S16, since this is the
beginning of the first iterative process, iterative
process counter K is set to one in step S42. Then, in



step S44 the specimen electrode counter i is set to one.

In step S46, the PC 10 accesses the specimen electrode voltages V_{i+1} and V_{i-1} determined in step S10
5 for electrodes $i+1$ and $i-1$, respectively, adjacent to electrode i . Then, in step S48 the PC 10 determines whether i equals one. If i equals one, then PC 10 sets, in step S50, the voltage V_{i-1} of electrode $i-1$ equal to the voltage V_{i+1} of electrode $i+1$ because
10 electrode $i-1$ does not exist.

After step S50, or if i does not equal 1, the PC 10 determines, in step S52, if i equals N (the total number of electrodes). If i equals N , then PC 10 sets, in step S54, the voltage V_{i+1} of electrode $i+1$ equal to
15 the voltage V_{i-1} of electrode $i-1$ because electrode $i+1$ does not exist.

The PC 10 determines, in step S56, the shifts, $V_{p(i+1)}$ and $V_{p(i-1)}$, in the peak voltage of the specimen electrode due to the voltages V_{i+1} and V_{i-1} of the
20 adjacent electrodes using voltages V_{i+1} and V_{i-1} and the Type II calibration curve. Shifts in the peak voltage of the specimen electrode, $V_{p(i+1)}$ and $V_{p(i-1)}$, are read from the Type II calibration curve using the adjacent electrode voltages V_{i+1} and V_{i-1} , respectively. If a peak
25 voltage of the Type II calibration curve does not match the measured peak voltage, then the PC 10 interpolates the shift in specimen electrode peak voltage based on the Type II calibration curve values greater than and less than the measured peak voltage.

30 Then in step S58, PC 10 determines the average shift $V_{p(av)}$ according to the following equation:

$$V_{p(av)} = (V_{p(i-1)} + V_{p(i+1)}) * 0.5 \quad (1)$$

In step S60 the PC 10 accesses the specimen electrode voltage V_i determined in step S10
35 corresponding to electrode i , and reads the peak voltage $V_{p(i)}$ corresponding to the voltage V_i from the Type I calibration curve. As described previously, PC

10 interpolates to determine the peak voltage $V_{p(i)}$, when the Type I calibration curve does not match the voltage V_i .

5 In step S62, the PC 10 corrects the peak voltage $V_{p(i)}$, corresponding to voltage V_i by subtracting the average shift $V_{p(av)}$ from the peak voltage $V_{p(i)}$. The PC 10 then reads, in step S64, the corrected specimen electrode voltage for electrode i from the Type I calibration curve using the corrected peak voltage $V_{p(i)}$.

10 In step S66, the PC 10 determines and stores the amount of correction $V_{corr(i)}$ of the specimen electrode voltage for electrode i . The amount of correction $V_{corr(i)}$ is determined by subtracting the specimen electrode voltage V_i for electrode i in step S60 from
15 the corrected specimen electrode voltage for electrode i determined in step S64.

In step S68 the specimen electrode counter i is incremented by one, and in step S70 PC 10 determines whether all N electrodes have undergone the measurement
20 steps of S46-S66 (i.e., is $i > N$?).

If the answer to step S70 is yes, the PC 10 determines which of the correction amounts, V_{corr} , for the N electrodes is largest, $V_{corr(max)}$, in step S74. Then in step S76 the PC 10 determines if $V_{corr(max)}$ is less than
25 a predetermined tolerance value. The tolerance value will depend on the accuracy required for the corrected specimen voltage and the computation time incurred in performing the correction scheme. This value is also dependent on the increment step size chosen for the
30 retarding grid voltage V_r (typically not more than an order of magnitude smaller than the increment), as it will not make sense to correct the voltage to an accuracy which the calibration process is not able to give (again this depends on the accuracy of the
35 interpolation in reading values from the stored calibration curves). If the answer in step S76 is yes, then the corrected specimen electrode voltages for the

N electrodes determined in step S64 are determined as the quantitative voltage contrast measurements.

If the answer in step S76 is no, then the second iterative process begins with incrementing the
5 iterative process counter K in step S78, setting the measurement electrode counter to one in step S82, setting the specimen electrode voltage for electrode i+1 equal to the correction amount $V_{corr(i+1)}$ for electrode i+1 in step S86, and setting the specimen electrode
10 voltage for electrode i-1 equal to the correction amount $V_{corr(i-1)}$ for the electrode i-1 also in step S86.

After step S86 the second iterative process beings measurement processing at step S48.

If the answer in step S70 is no, then in step S72
15 it is determined if the iterative process counter K is greater than one. If the answer to step S72 is yes, then second iterative processing continues beginning at step S86. If the answer to step S72 is no, then first iterative processing continues beginning at step S46.

20 Figure 9 is a graph of the error in the measured specimen electrode voltage, as to Type I local field effects only, versus the actual specimen voltage V_s with the adjacent electrode voltages set to zero. Figure 9 provides a comparison between the conventional feedback
25 technique and three methods (A, B, and C) according to the present invention.

Method A is the method just described above with respect to Figures 1-4(c) (i.e., Neumann boundary conditions are used). Method B is the same as method
30 A except that in step S50, V_{i-1} is set to zero and in step S54, V_{i+1} is set to zero (i.e., Dirichlet boundary conditions). Method C is also the same as method B except that step S86 is omitted. As seen from Figure 9, the present invention provides for greatly increased
35 accuracy in measuring quantitative voltage contrast.

Figure 10 is a scatter plot showing the error in the measured electrode voltage, when both Type I and



Type II local field effects are present, versus the actual electrode voltage for the specimen and adjacent electrodes when method B is followed. As with Figure 9, Figure 10 illustrates the accuracy obtained by the present invention in quantitative voltage contrast measurements.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modification as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

I/we claim:

- 1 1. A method of measuring quantitative voltage
- 2 contrast comprising the steps of:
- 3 (a) outputting instructions from a processor to an
- 4 energy analyzer and scanning electron microscope;
- 5 (b) locating an electron beam of said scanning
- 6 electron microscope on a specimen electrode of a
- 7 specimen structure based on said instructions;
- 8 (c) varying a grid voltage of said energy analyzer
- 9 in accordance with said instructions;
- 10 (d) detecting secondary electron emission from
- 11 said specimen electrode with a detector of said
- 12 scanning electron microscope;
- 13 (e) determining a measured peak voltage of said
- 14 specimen electrode based on output from said detector;
- 15 (f) obtaining a specimen electrode voltage .
- 16 corrected for type I local field effect error using
- 17 said measured peak voltage and a type I calibration
- 18 curve, said type I calibration curve representing peak
- 19 voltage versus specimen electrode voltage; and



20 (g) correcting for type II local field effect
21 error in output of said step (f) based on a type II
22 calibration curve, said type II calibration curve
23 representing a shift in specimen electrode peak voltage
24 versus adjacent electrode voltage.

1 2. The method of claim 1, wherein said step (c)
2 varies a grid voltage of a retarding grid of said
3 energy analyzer.

1 3. The method of claim 1, further comprising the
2 steps of:

3 (h) preparing said type I calibration curve; and

4 (i) preparing said type II calibration curve.

1 4. The method of claim 3, wherein said step (h)
2 comprises the steps of:

3 (h1) providing a three-electrode, unpassivated
4 reference structure, said three electrodes including a
5 center electrode and two adjacent electrodes;

6 (h2) applying, via said energy analyzer, a fixed
7 voltage to said center electrode and a zero voltage to
8 said two adjacent electrodes based on said
9 instructions;

10 (h3) varying said grid voltage in accordance with
11 said instructions;

12 (h4) determining a reference peak voltage based on
13 output from said detector;



14 (h5) storing said reference peak voltage with
15 respect to said fixed voltage.

1 5. The method of claim 3, wherein said step (i)
2 comprises the steps of:

3 (i1) providing a three-electrode, unpassivated
4 reference structure, said three electrodes including a
5 center electrode and a first and second adjacent
6 electrode adjacent to said center electrode;

7 (i2) applying, via said energy analyzer, a fixed
8 voltage to said first adjacent electrode and a zero
9 voltage to said center electrode and said second
10 adjacent electrode based on said instructions;

11 (i3) varying said grid voltage in accordance with
12 said instructions;

13 (i4) determining a reference peak voltage based on
14 output from said detector;

15 (i5) temporarily setting said first adjacent
16 electrode to a base voltage;

17 (i6) measuring a base peak voltage using output
18 from said detector;

19 (i7) subtracting said base peak voltage from said
20 reference peak voltage to obtain said reference peak
21 voltage shift; and

22 (i8) storing said reference peak voltage shift
23 with respect to said fixed voltage.



1 6. The method of claim 1, wherein said step (e)
2 comprises the steps of:

3 (e1) producing a curve of output from said step
4 (d) versus said grid voltage; and
5 (e2) determining said peak voltage as an
6 inflection point in said curve.

1 7. The method of claim 4, wherein said step (h4)
2 comprises the steps of:

3 (h41) producing a curve of output from said
4 detector versus said grid voltage; and
5 (h42) determining said reference peak voltage as
6 an inflection point in said curve.

1 8. The method of claim 5, wherein said step (i4)
2 comprises the steps of:

3 (i41) producing a curve of output from said
4 detector versus said grid voltage; and
5 (i42) determining said reference peak voltage as
6 an inflection point in said curve.

1 9. The method of claim 1, wherein said step (f)
2 includes the step of reading said specimen electrode
3 voltage from said type I calibration curve using said
4 measured peak voltage.

1 10. The method of claim 1, wherein said step (g)
2 comprises the steps of:



3 (g1) calculating an average peak voltage shift for
4 said specimen electrode using said type II calibration
5 curve;

6 (g2) reading a peak voltage of said specimen
7 electrode from said type I calibration curve using said
8 specimen electrode voltage;

9 (g3) correcting said read peak voltage using said
10 average peak voltage shift to produce a corrected peak
11 voltage; and

12 (g4) reading a corrected specimen electrode
13 voltage from said type I calibration curve using said
14 corrected peak voltage.

1 11. The method of claim 10, wherein said step
2 (g1) includes the steps of:

3 (g11) obtaining a first and a second specimen
4 electrode voltage for a first and a second electrode
5 adjacent to said specimen electrode, respectively;

6 (g12) reading first and second peak voltage shifts
7 corresponding to said first and second specimen
8 electrode voltages from said type II calibration curve;
9 and

10 (g13) calculating an average of said first and
11 second peak voltages shifts.

1 12. The method of claim 10, wherein said step
2 (g3) includes the step of (g31) subtracting said



3 average peak voltage shift from said read peak voltage
4 shift.

1 13. The method of claim 1, wherein said step (g)
2 comprises the steps of:

3 (g1) reading, from said type II calibration curve,
4 a first and second peak voltage shift corresponding to
5 a first and second electrode adjacent said specimen
6 electrode; and

7 (g2) calculating an average peak voltage shift for
8 said specimen electrode using said first and second
9 peak voltage shifts;

10 (g3) reading a peak voltage of said specimen
11 electrode from said type I calibration curve using said
12 specimen electrode voltage;

13 (g4) correcting said read peak voltage using said
14 average peak voltage shift to produce a corrected peak
15 voltage; and

16 (g5) reading a corrected specimen electrode
17 voltage from said type I calibration curve using said
18 corrected peak voltage.

1 14. The method of claim 13, wherein each
2 electrode of said specimen structure is treated as a
3 specimen electrode, and further comprising the step of:

4 (h) repeating steps (b), (c), (d), (e) and (f) for
5 each electrode of said specimen structure; and



6 (i) repeating step (g) for each electrode of said
7 specimen structure.

1 15. The method of claim 14, wherein
2 said step (g) further includes the step of (g6)
3 determining a correction amount for said specimen
4 electrode; and further comprising the step of,
5 (j) determining a maximum one of said correction
6 amounts;
7 (k) comparing output of said step (j) to a
8 threshold amount; and
9 (l) re-correcting for said type II local field
10 effect error in output of said step (g5) based on a
11 result of said step (k).

1 16. The method of claim 15, wherein said step
2 (g6) includes the step of (g61) subtracting the
3 specimen electrode voltage from the corrected specimen
4 electrode voltage.

1 17. The method of claim 15, wherein said step (l)
2 comprises the steps of:
3 (11) setting said first and second peak voltage
4 shifts equal to said correction amount for said first
5 and second electrodes adjacent said specimen electrode;
6 and
7 (12) repeating steps (g1)-(g5).



1 18. An apparatus for measuring quantitative
2 voltage contrast comprising:
3 means for outputting instructions to an energy
4 analyzer and scanning electron microscope;
5 means for locating an electron beam of said
6 scanning electron microscope on a specimen electrode of
7 a specimen structure based on said instructions;
8 means for varying a grid voltage of said energy
9 analyzer in accordance with said instructions;
10 means for detecting secondary electron emission
11 from said specimen electrode;
12 means for determining a measured peak voltage of
13 said specimen electrode based on output from said means
14 for detecting;
15 means for obtaining a specimen electrode voltage
16 corrected for type I local field effect error using
17 said measured peak voltage and a type I calibration
18 curve, said type I calibration curve representing peak
19 voltage versus specimen electrode voltage; and
20 means for correcting for type II local field
21 effect error in output of said means for obtaining
22 based on a type II calibration curve, said type II
23 calibration curve representing a shift in specimen
24 electrode peak voltage versus adjacent electrode
25 voltage.



1 19. The apparatus of claim 18, wherein said means
2 for determining includes a lock-in amplifier means for
3 producing a curve of output from said means for
4 detecting versus said grid voltage, and for determining
5 said peak voltage as an inflection point in said curve.

1 20. The apparatus of claim 18, wherein said means
2 for obtaining includes memory means for storing said
3 type I calibration curve; and means for reading said
4 specimen electrode voltage from said type I calibration
5 curve stored in said memory means using said measured
6 peak voltage.

1 21. The apparatus of claim 18, wherein said means
2 for correcting for type II local field effect error
3 comprises:

4 means for calculating an average peak voltage
5 shift for said specimen electrode using said type II
6 calibration curve;

7 first means for reading a peak voltage of said
8 specimen electrode from said type I calibration curve
9 using said specimen electrode voltage;

10 means for correcting said read peak voltage using
11 said average peak voltage shift to produce a corrected
12 peak voltage; and

13 second means for reading a corrected specimen
14 electrode voltage from said type I calibration curve
15 using said corrected peak voltage.



1 22. The apparatus of claim 21, wherein means for
2 calculating includes:

3 means for obtaining a first and a second specimen
4 electrode voltage for a first and a second electrode
5 adjacent to said specimen electrode, respectively;

6 means for reading first and second peak voltage
7 shifts corresponding to said first and second specimen
8 electrode voltages from said type II calibration curve;
9 and

10 means for averaging said first and second peak
11 voltages shifts.

1 23. The apparatus of claim 21, wherein said
2 means for correcting subtracts said average peak
3 voltage shift from said read peak voltage shift.

1 24. An apparatus for producing a type I
2 calibration curve, comprising:

3 a three-electrode, unpassivated reference
4 structure, said three electrodes including a center
5 electrode and two adjacent electrodes, said reference
6 structure being disposed in an energy analyzer of a
7 scanning electron microscope;

8 means for applying, via said energy analyzer, a
9 fixed voltage to said center electrode and a zero
10 voltage to said two adjacent electrodes;



11 means for varying a grid voltage of said energy
12 analyzer;

13 means for detecting secondary electron emission
14 from said reference structure;

15 means for determining a reference peak voltage
16 based on output from said means for detecting; and

17 means for storing said reference peak voltage with
18 respect to said fixed voltage.

1 25. An apparatus for producing a type I
2 calibration curve, comprising:

3 a three-electrode, unpassivated reference
4 structure, said three electrodes including a center
5 electrode and a first and second adjacent electrode
6 adjacent to said center electrode, said reference
7 structure being disposed in an energy analyzer of a
8 scanning electron microscope;

9 means for applying, via said energy analyzer, a
10 fixed voltage to said first adjacent electrode and a
11 zero voltage to said center electrode and said second
12 adjacent electrode;

13 means for varying a grid voltage of said energy
14 analyzer;

15 means for detecting secondary electron emission
16 from said reference structure;

17 means for determining a reference peak voltage
18 based on output from said means for detecting;



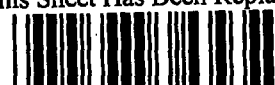
19 means for temporarily setting said first adjacent
20 electrode to a base voltage;
21 means for measuring a base peak voltage using
22 output from said means for detecting;
23 means for subtracting said base peak voltage from
24 said reference peak voltage to obtain said reference
25 peak voltage shift; and
26 means for storing said reference peak voltage
27 shift with respect to said fixed voltage.



ABSTRACT OF THE DISCLOSURE

In a method and apparatus for measuring quantitative voltage contrast, an electron beam of the scanning electron microscope is located on a specimen electrode, and a grid voltage of an energy analyzer of the scanning electron microscope is varied. A detector detects secondary electron emission from the specimen electrode. A measured peak voltage of the specimen electrode is determined based on output from the detector. A specimen electrode voltage corrected for type I local field effect error is then obtained using the measured peak voltage and a type I calibration curve. The type I calibration curve represents peak voltage versus specimen electrode voltage. Type II local field effect error in the specimen electrode voltage is then corrected based on a type II calibration curve. The type II calibration curve represents a shift in specimen electrode peak voltage versus adjacent electrode voltage.

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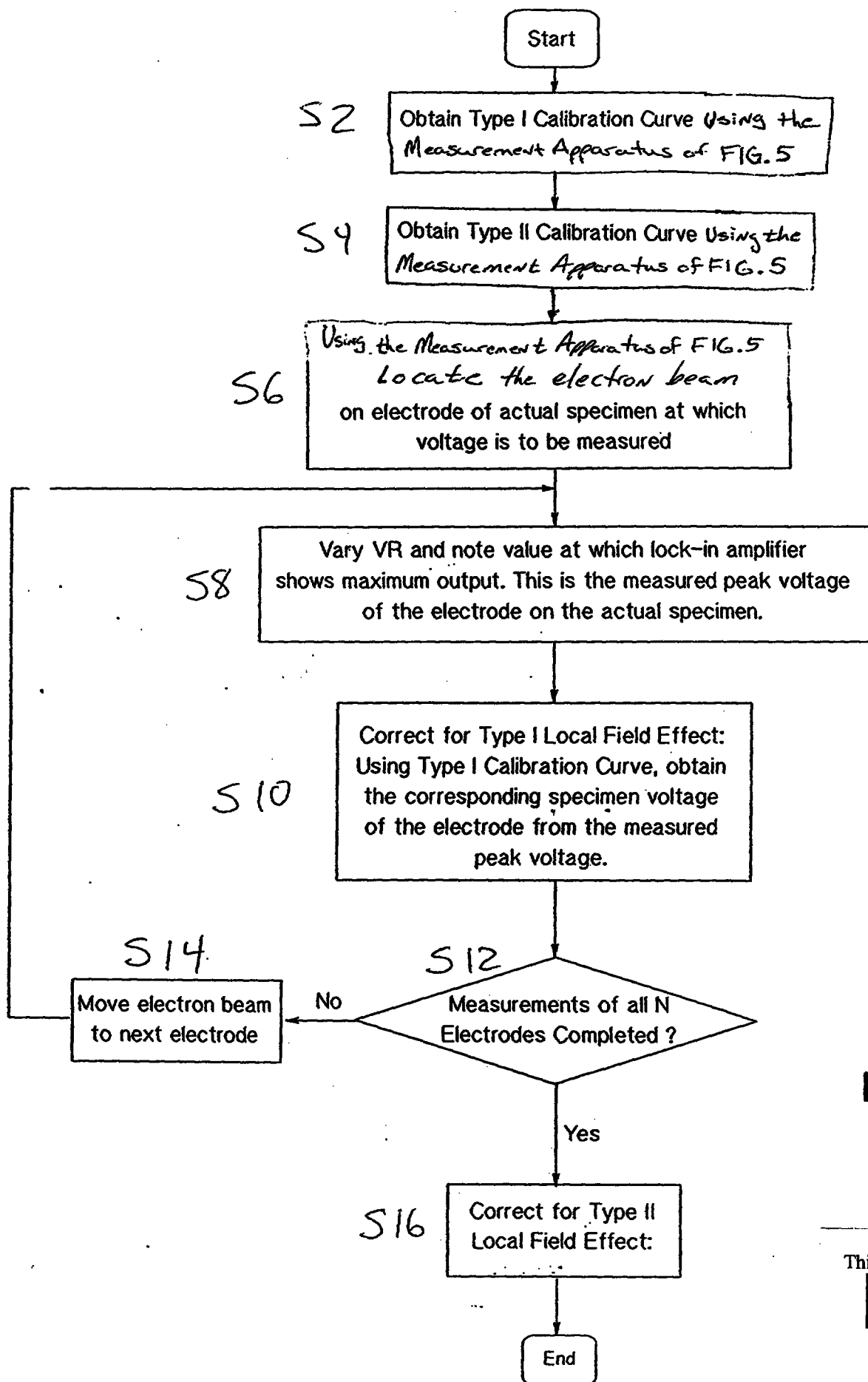


Figure 1

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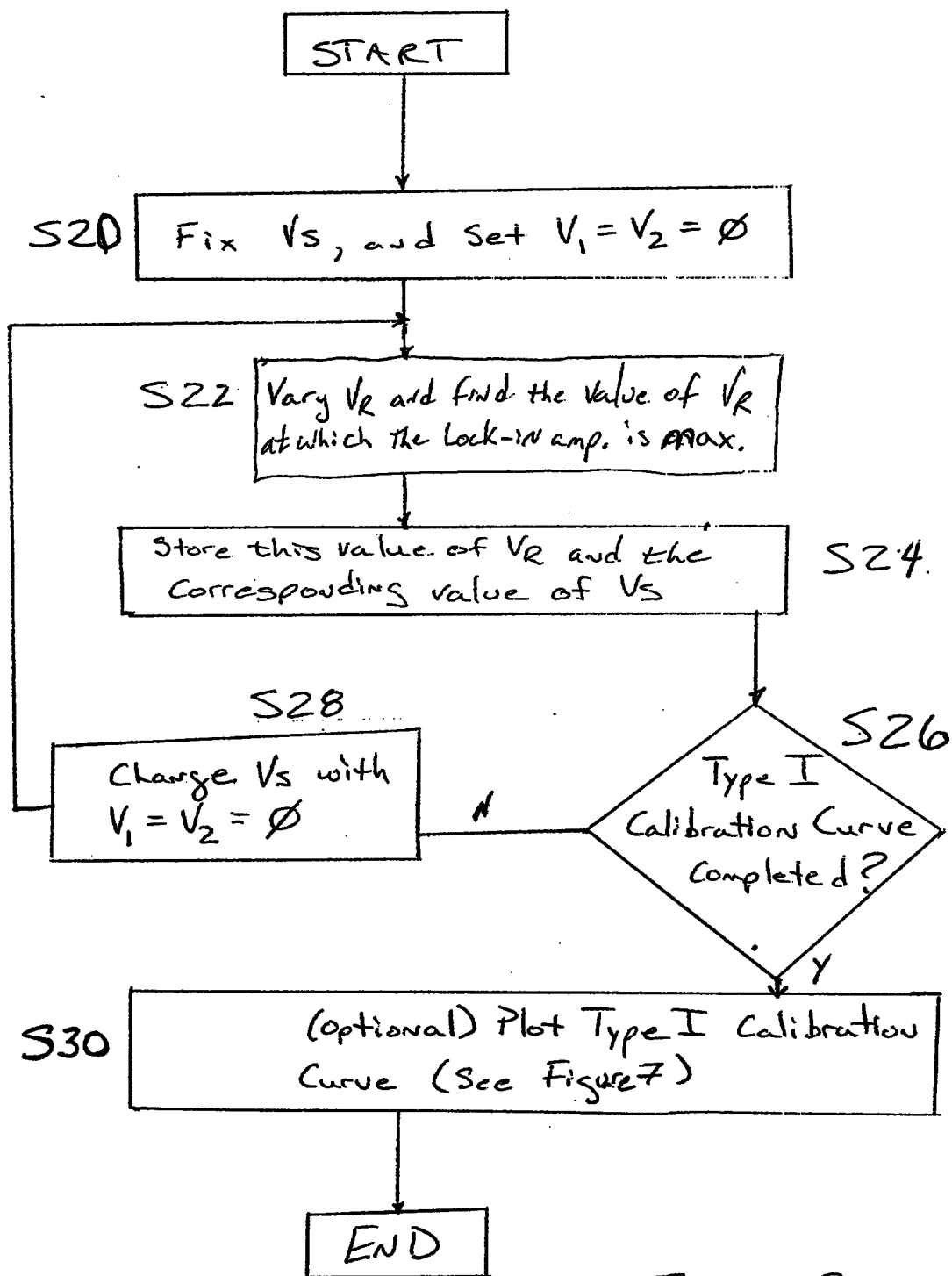


Figure 2

(Step S2)

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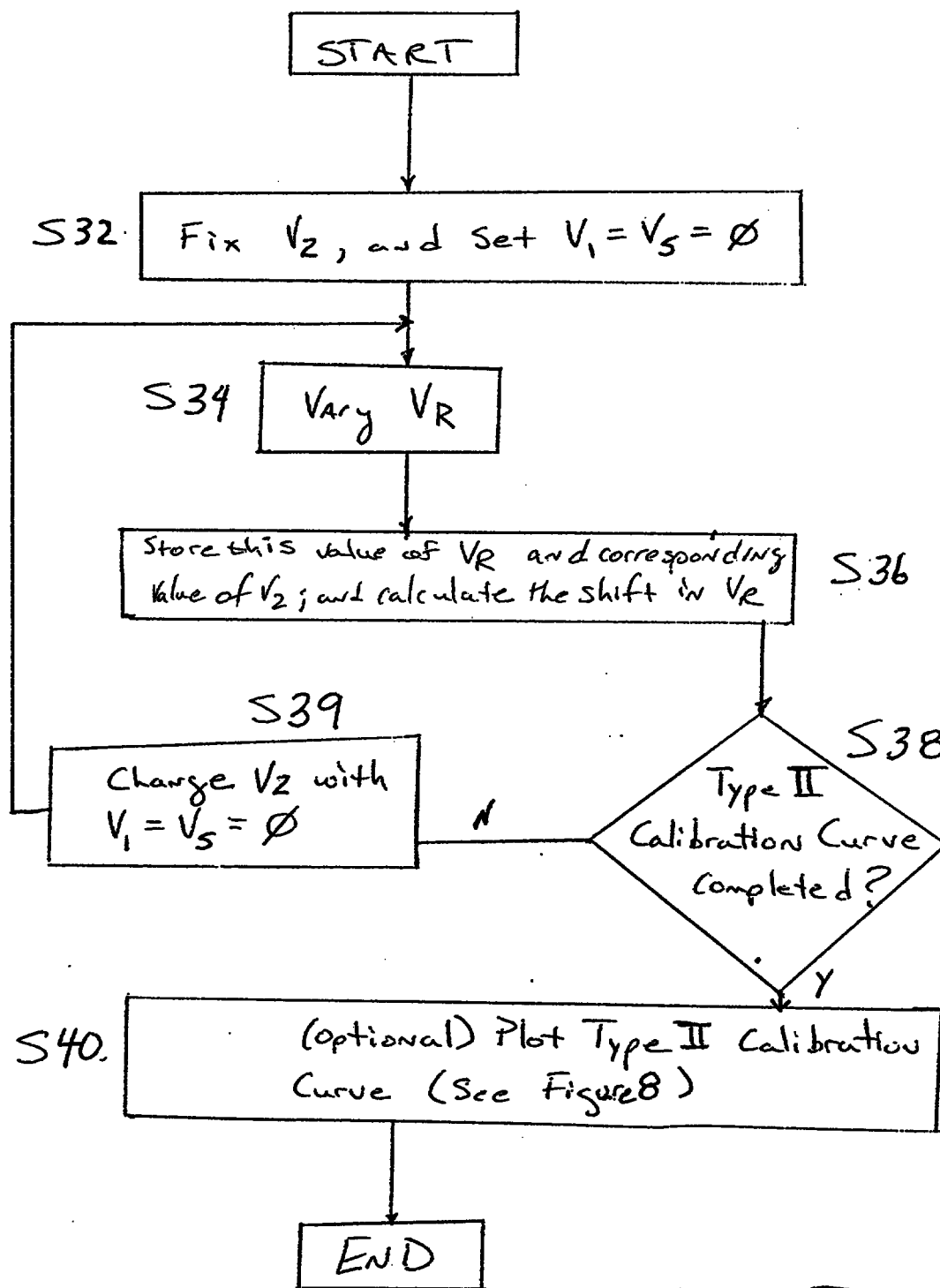


Figure 3

(Step S4.)



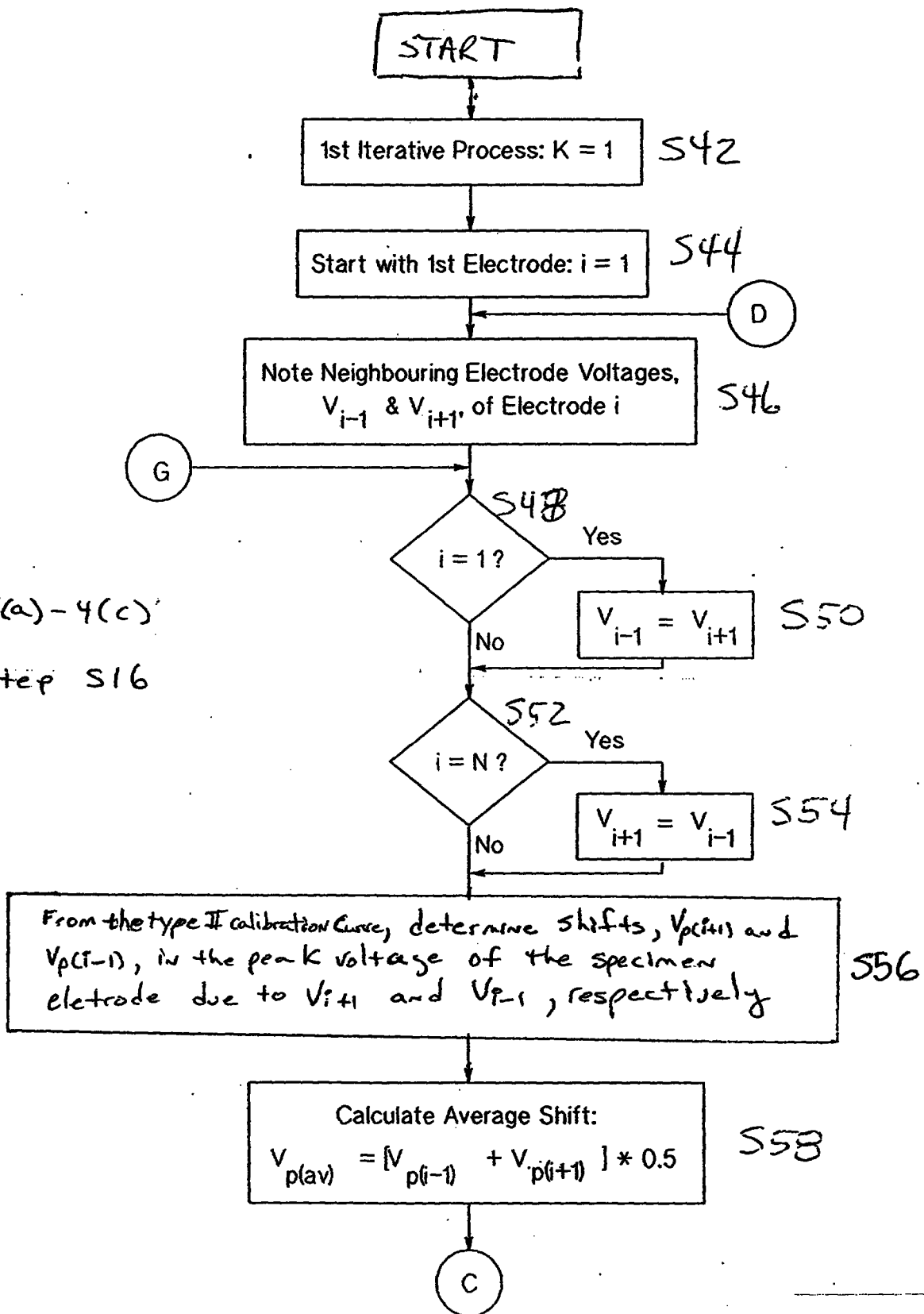


Figure 4(a)

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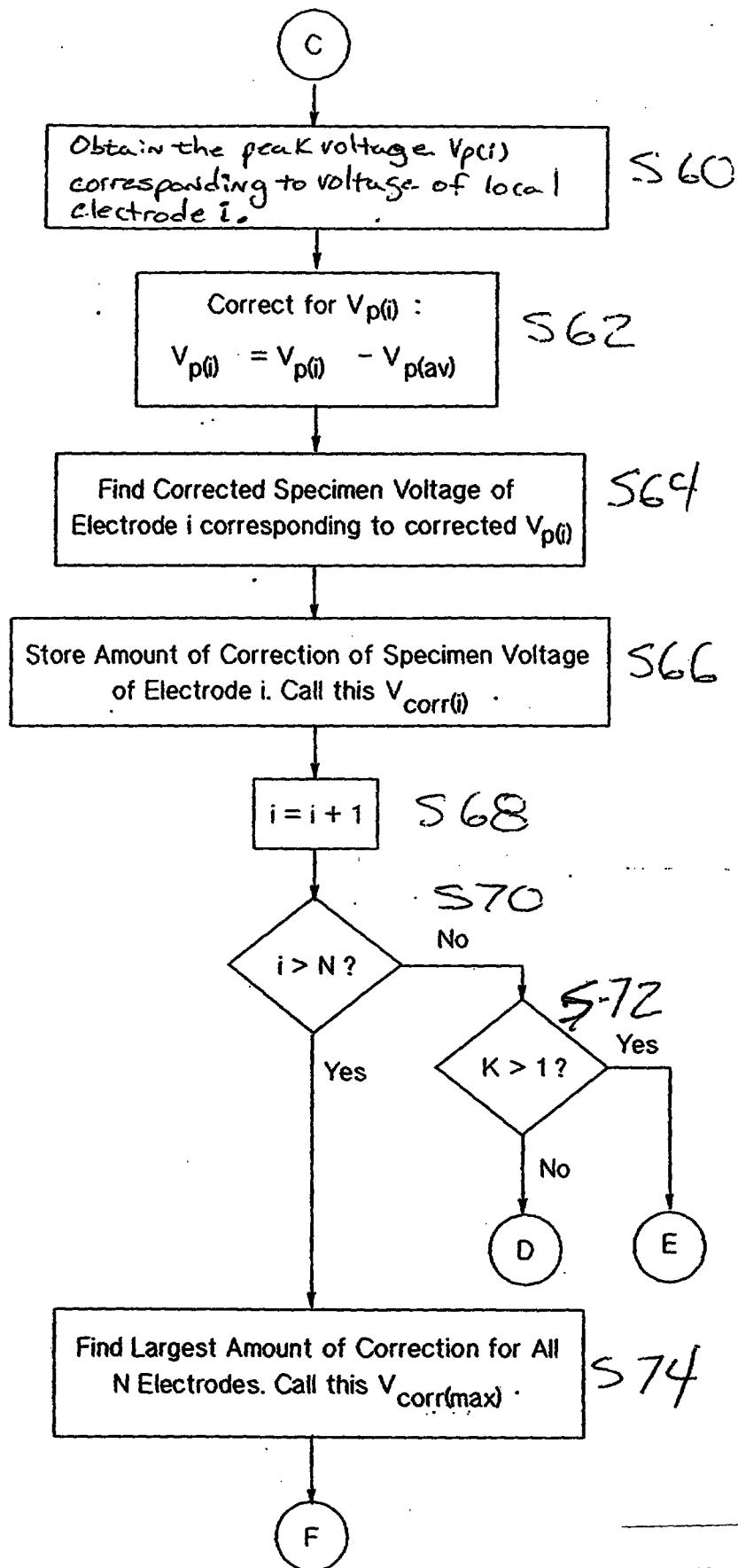


Figure 4(b)

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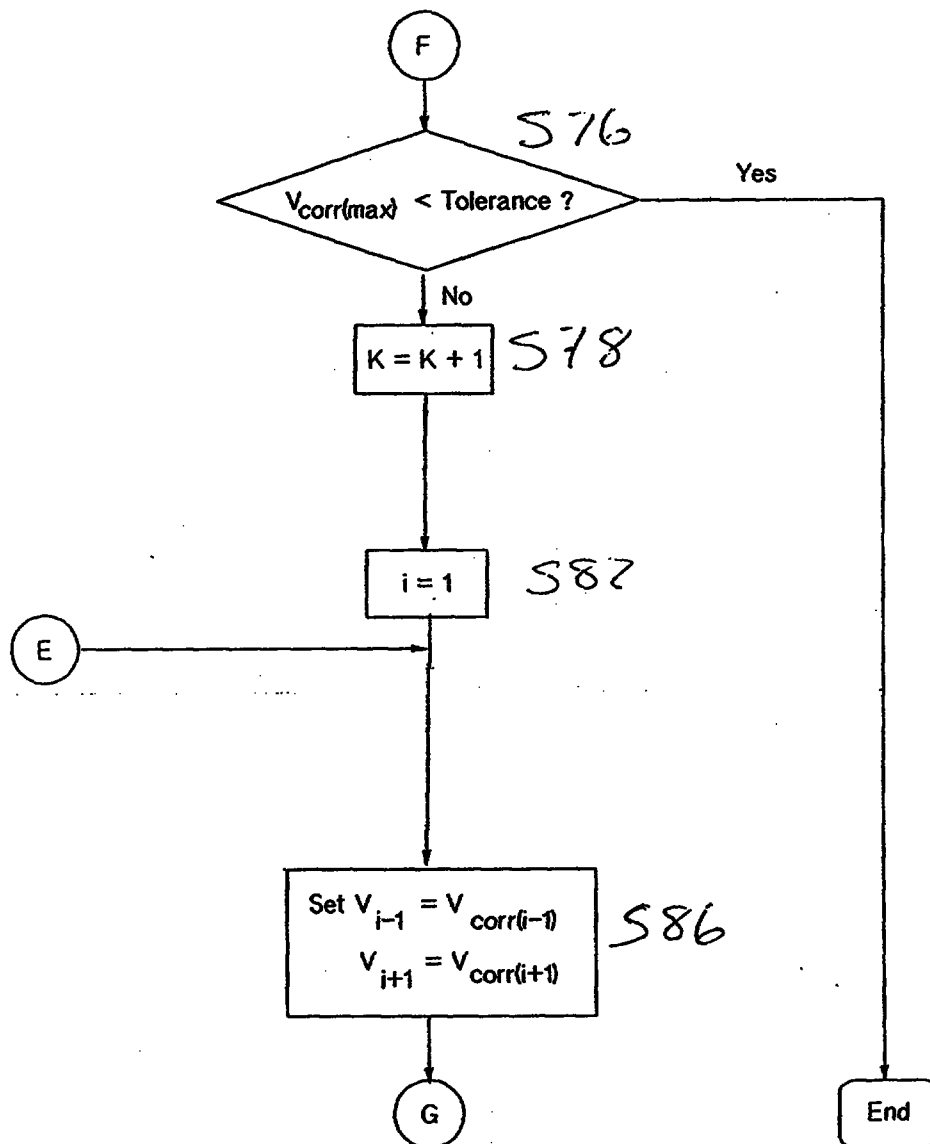


Figure 4(c)

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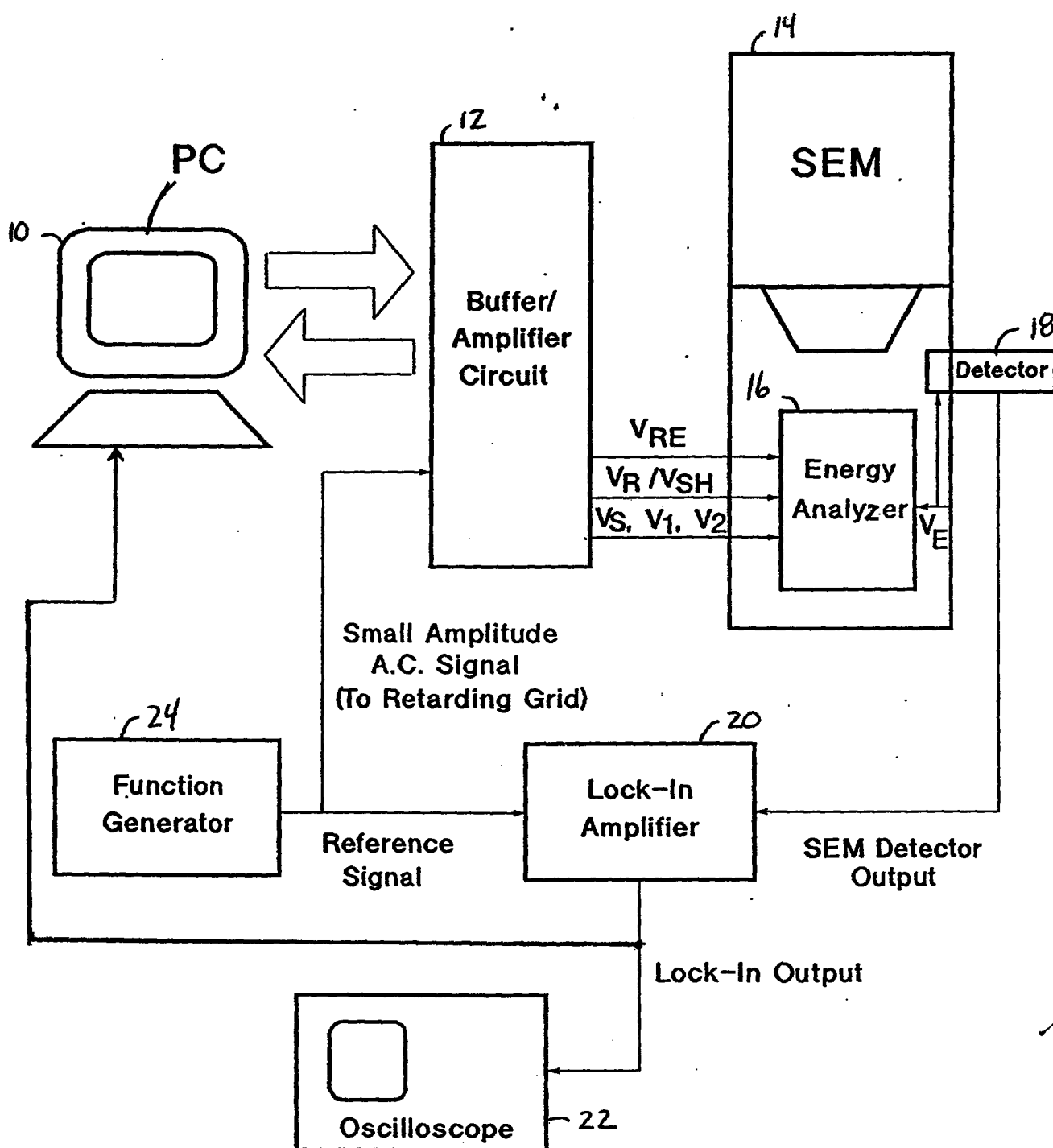
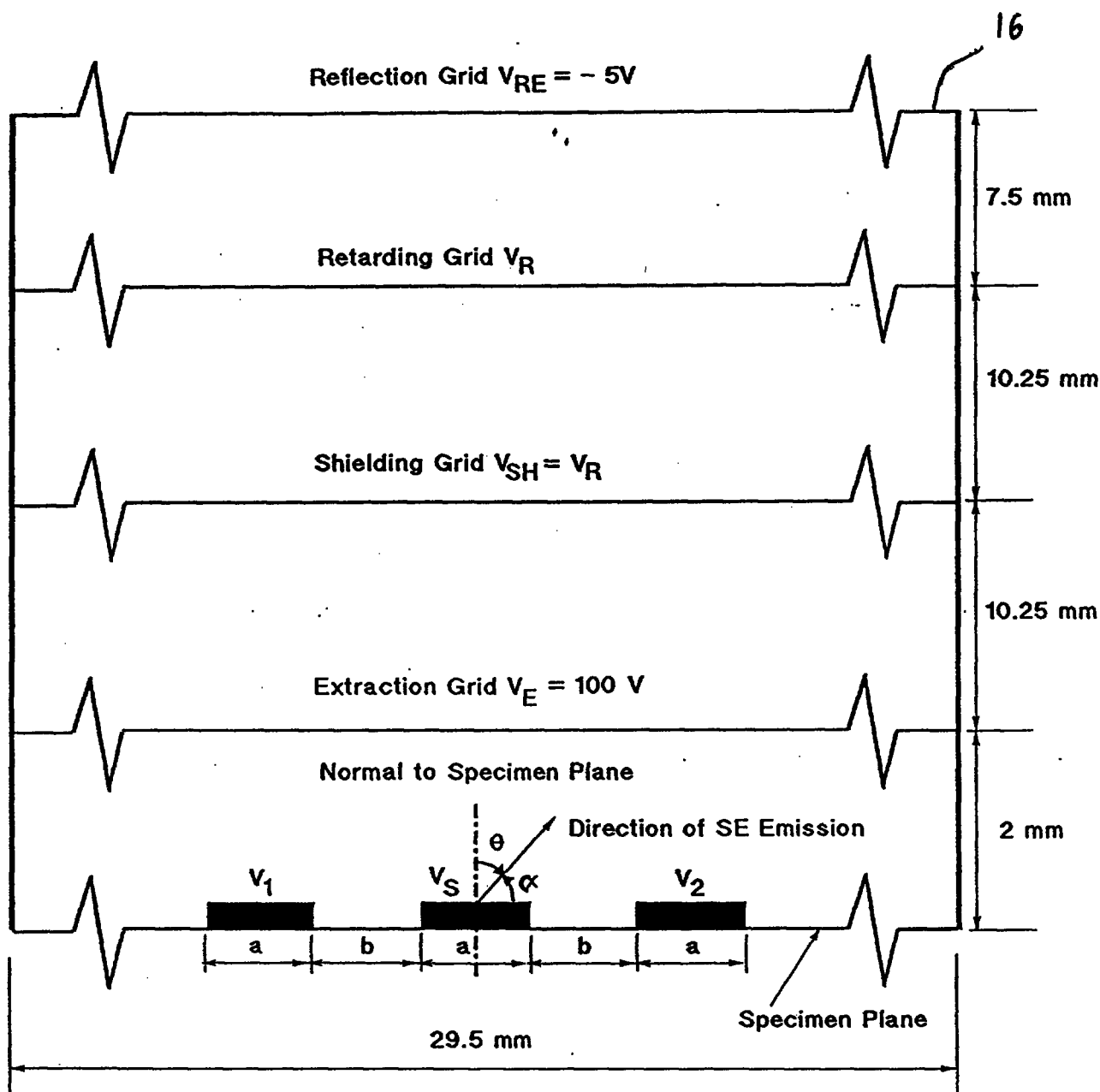


Figure 5

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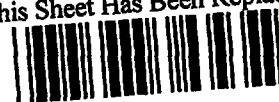


a = Electrode Width

b = Separation Between Electrodes

Figure 6

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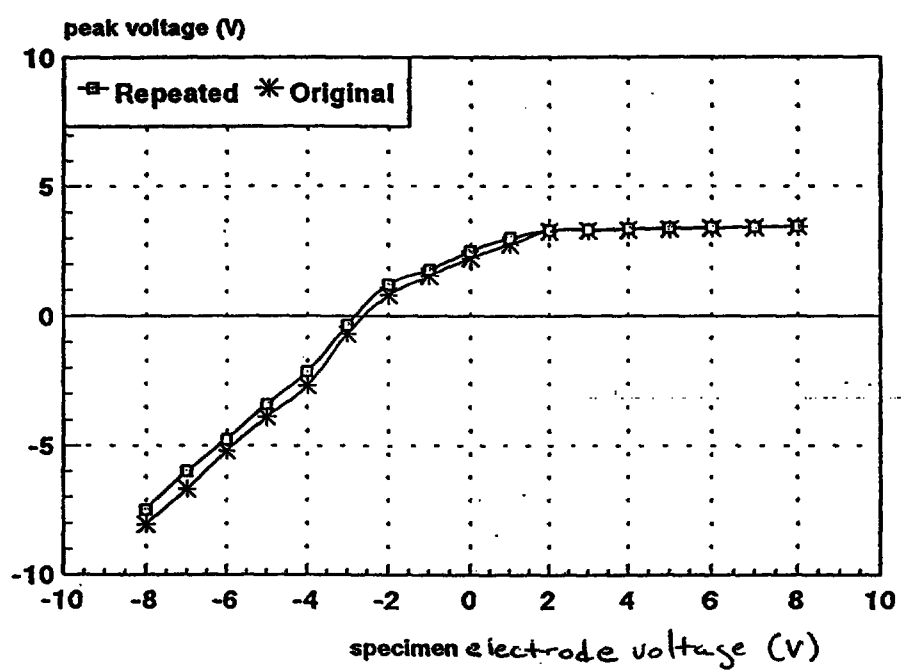
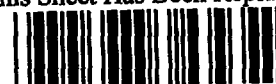


Figure 7

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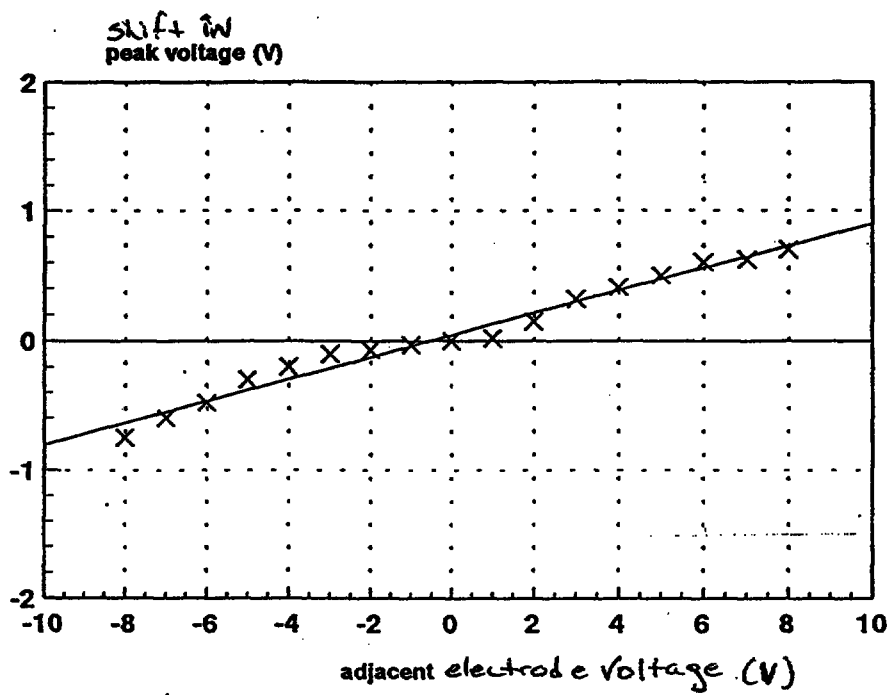


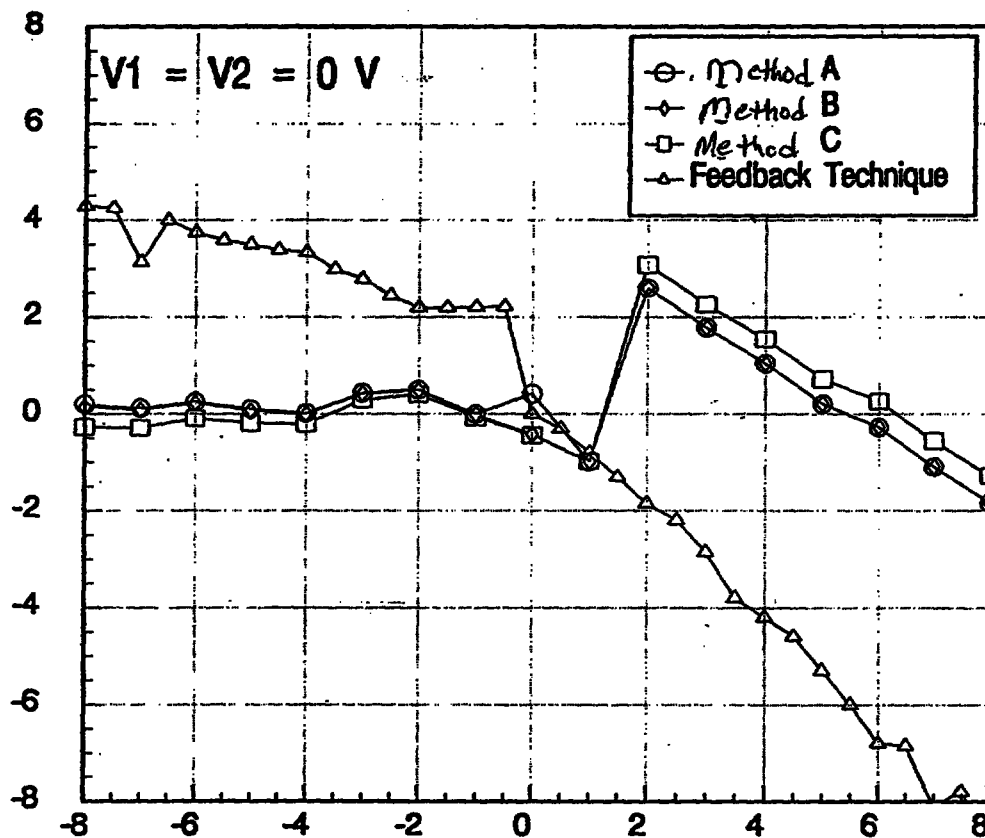
Figure 8

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Error in Measured Specimen Voltage (V)



ACTUAL SPECIMEN ELECTRODE Voltage V_s (V)

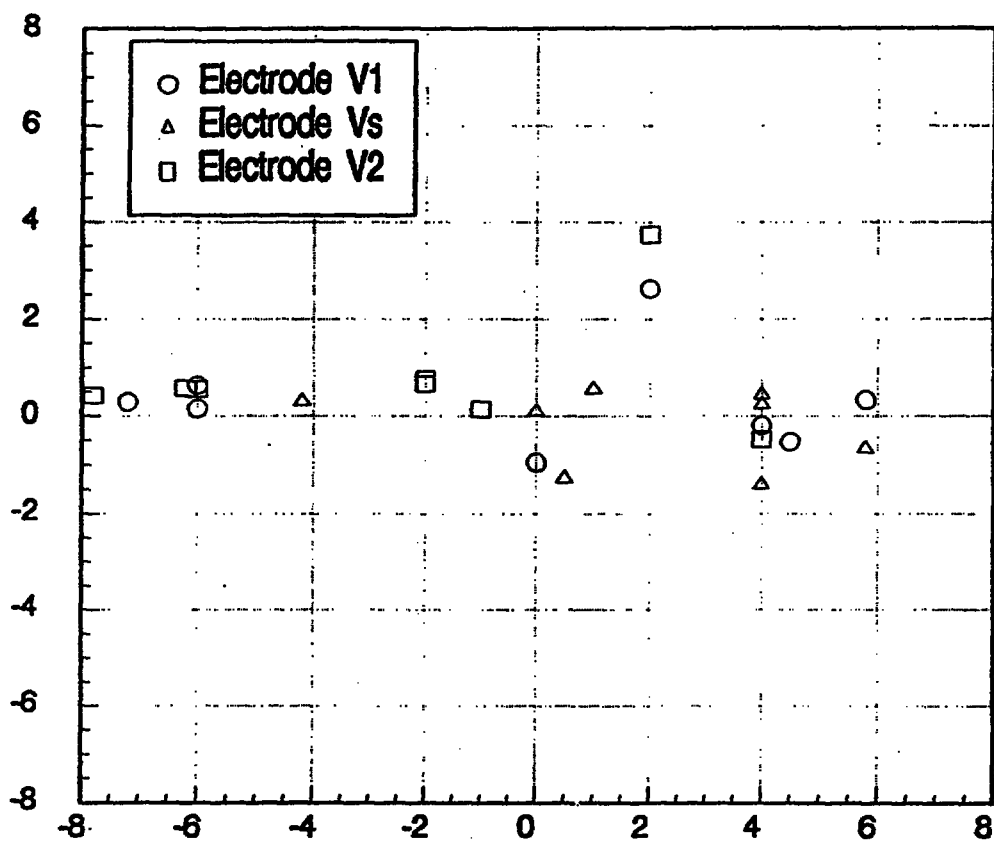
Figure 9

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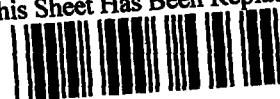
Error in Corrected Electrode Voltage (V)



Actual Electrode Voltage (V)

Figure 10

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ABSTRACT

A method and apparatus for measuring quantitative voltage contrast are described in which an electron beam of the scanning electron microscope is located on a specimen electrode, and a grid voltage of an energy analyzer of the scanning electron microscope is varied. A detector detects secondary electron emission from the specimen electrode. A measured peak voltage of the specimen electrode is determined based on output from the detector. A specimen electrode voltage corrected for type I local field effect error is then obtained using the measured peak voltage and a type I calibration curve. The type I calibration curve represents peak voltage versus specimen electrode voltage. Type II local field effect error in the specimen electrode voltage is then corrected based on a type II calibration curve. The type II calibration curve represents a shift in specimen electrode peak voltage versus adjacent electrode voltage. (Fig. 1)

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determining a measured peak voltage of said specimen electrode based on output from said means for detecting; means for obtaining a specimen electrode voltage corrected for type I local field effect error
5 using said measured peak voltage and a type I calibration curve, said type I calibration curve representing peak voltage versus specimen electrode voltage; and means for correcting for type II local field effect error in output of said means for
10 obtaining based on a type II calibration curve, said type II calibration curve representing a shift in specimen electrode peak voltage versus adjacent electrode voltage.

These and other related objectives of the present
15 invention will become more readily apparent from the detailed description given hereafter. It should, however, be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of
20 illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

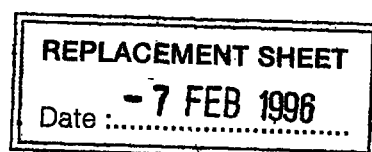
BRIEF DESCRIPTION OF THE DRAWINGS

25 The present invention will become more fully understood from the detailed description here-in-below and the accompanying drawings which are given by way of illustration only, and thus do not limit the present invention.

30 Figures 1-4-c are flow charts illustrative of the method according to the present invention;

Figure 5 is a block diagram of the measurement apparatus according to the present invention;

Figure 6 is a schematic diagram of the energy
35 analyzer according to the present invention;



lock-in amplifier 20 a voltage representing the detected secondary electrons. The lock-in amplifier 20 also receives the small a.c. signal from the function generator 24 as a reference signal. The lock-in
5 amplifier 20 differentiates the curve representing the output of detector 18 versus the retarding grid voltage V_R . The output of the lock-in amplifier 20 corresponds to the energy distribution of secondary electron emissions. The shift in the peak of the secondary
10 electron energy distribution provides information on the voltage of the electrodes. The retarding grid voltage V_R where the output of the lock-in amplifier 20 is maximum indicates the peak of the secondary electron distribution. The lock-in amplifier 20 may be a
15 commercially available lock-in amplifier such as the SR-530 Lock-in Amplifier from Stanford Research Systems.

The PC 10 receives the output of the lock-in amplifier 20, and measures the quantitative voltage
20 contrast based thereon. The output of the lock-in amplifier 20 can also be monitored using oscilloscope 22.

The quantitative voltage contrast measurement performed by the measurement apparatus of Figure 5 will
25 now be described with reference to the flow charts of Figures 1-4-c .

The flow chart of Figure 1 shows the method for making quantitative voltage contrast measurements. In step S2 a Type I calibration curve is obtained. The
30 Type I calibration curve, which is a plot of peak voltage versus specimen electrode voltage, will be used in later steps for correcting Type I local field effect errors.

Figure 2 is a flow chart showing the method for
35 obtaining the Type I calibration curve. The description of the flow chart shown in Figure 2 will be made in association with an example of a Type I

scheme for Type II local field effects, elaborated in the flow chart of Figures 4-a -4-c , includes two iterative processes.

In the first iterative process, the voltages of
5 the adjacent electrodes for each of the N electrodes are examined, and the shift in the peak voltage due to the voltages of the adjacent electrodes are determined for each of the N electrodes using the Type II calibration curve. The PC 10 then determines a
10 corrected peak voltage for each of the N electrodes using the determined shifts in the peak voltage, and determines the actual N specimen electrode voltages therefrom. If the largest peak voltage correction amount falls below a predetermined tolerance (i.e.
15 achieves a desired measurement accuracy), then the quantitative voltage contrast measurement process ends; otherwise, the PC 10 begins a second iterative process.

The second iterative process differs from the first iterative process in that the peak voltage
20 correction amounts of the adjacent electrodes are used, instead of the voltages of the adjacent electrodes, to determine the shifts in the peak voltage for each of the N electrodes. The remainder of the quantitative voltage contrast measurement process continues as in
25 the first iterative process. If, however, the largest peak voltage correction amount of the second iterative process exceeds the predetermined tolerance, the second iterative process is repeated, and will only terminate upon reaching the desired measurement accuracy. Each
30 successive iteration of the second iterative process uses the peak voltage correction amounts of the previous iteration of the second iterative process.

The first and second iterative process will now be described in detail with respect to Figures 4-a -4-c .
35 At the beginning of step S16, since this is the beginning of the first iterative process, iterative process counter K is set to one in step S42. Then, in

N electrodes determined in step S64 are determined as the quantitative voltage contrast measurements.

If the answer in step S76 is no, then the second iterative process begins with incrementing the
5 iterative process counter K in step S78, setting the measurement electrode counter to one in step S82, setting the specimen electrode voltage for electrode $i+1$ equal to the correction amount $V_{\text{corr}(i+1)}$ for electrode $i+1$ in step S86, and setting the specimen electrode
10 voltage for electrode $i-1$ equal to the correction amount $V_{\text{corr}(i-1)}$ for the electrode $i-1$ also in step S86.

After step S86 the second iterative process beings measurement processing at step S48.

If the answer in step S70 is no, then in step S72
15 it is determined if the iterative process counter K is greater than one. If the answer to step S72 is yes, then second iterative processing continues beginning at step S86. If the answer to step S72 is no, then first iterative processing continues beginning at step S46.

20 Figure 9 is a graph of the error in the measured specimen electrode voltage, as to Type I local field effects only, versus the actual specimen voltage V_s with the adjacent electrode voltages set to zero. Figure 9 provides a comparison between the conventional feedback
25 technique and three methods (A, B, and C) according to the present invention.

Method A is the method just described above with respect to Figures 1-4-c, (i.e., Neumann boundary conditions are used). Method B is the same as method
30 A except that in step S50, V_{i-1} is set to zero and in step S54, V_{i+1} is set to zero (i.e., Dirichlet boundary conditions). Method C is also the same as method B except that step S86 is omitted. As seen from Figure 9, the present invention provides for greatly increased
35 accuracy in measuring quantitative voltage contrast.

Figure 10 is a scatter plot showing the error in the measured electrode voltage, when both Type I and

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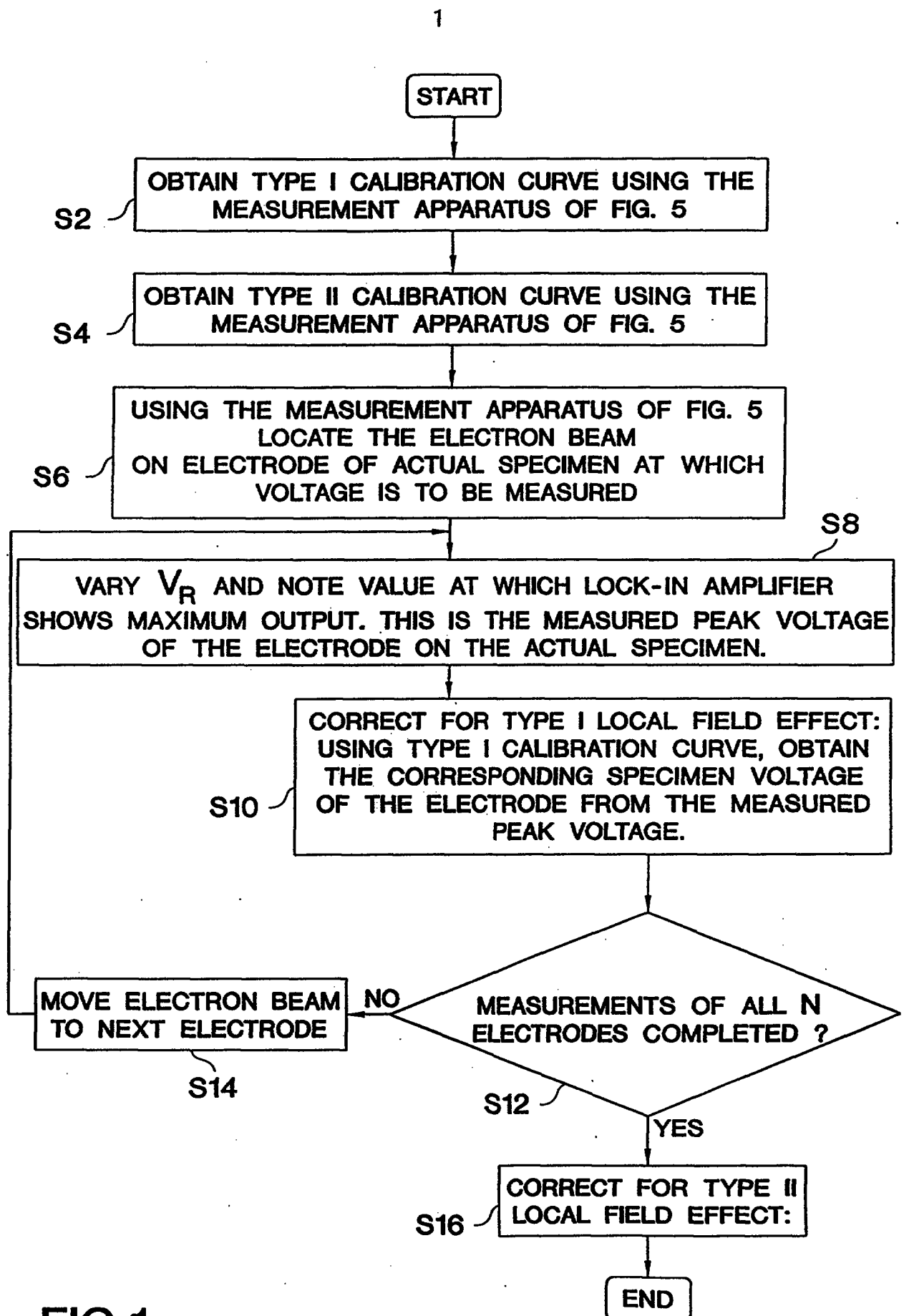
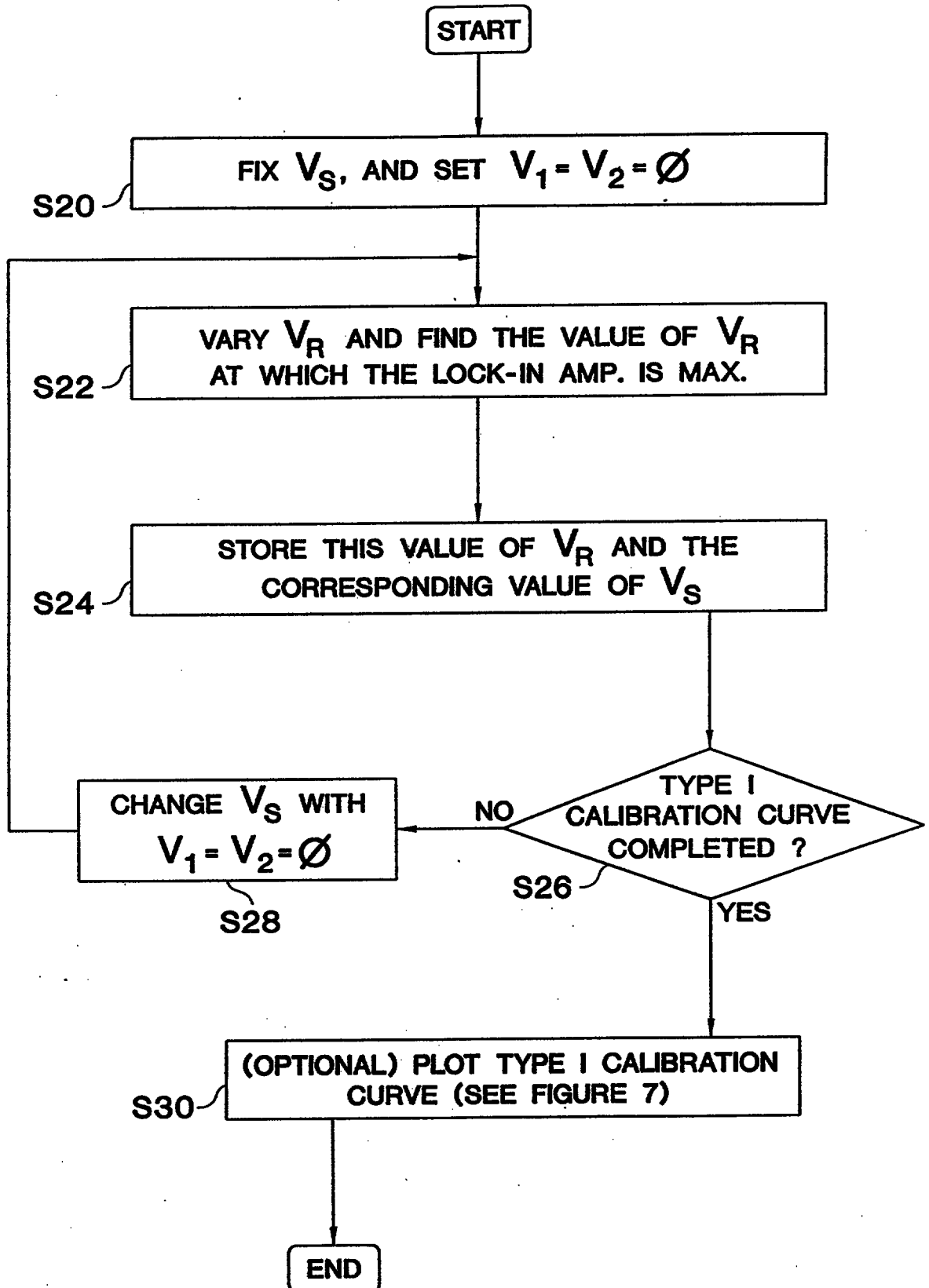


FIG.1

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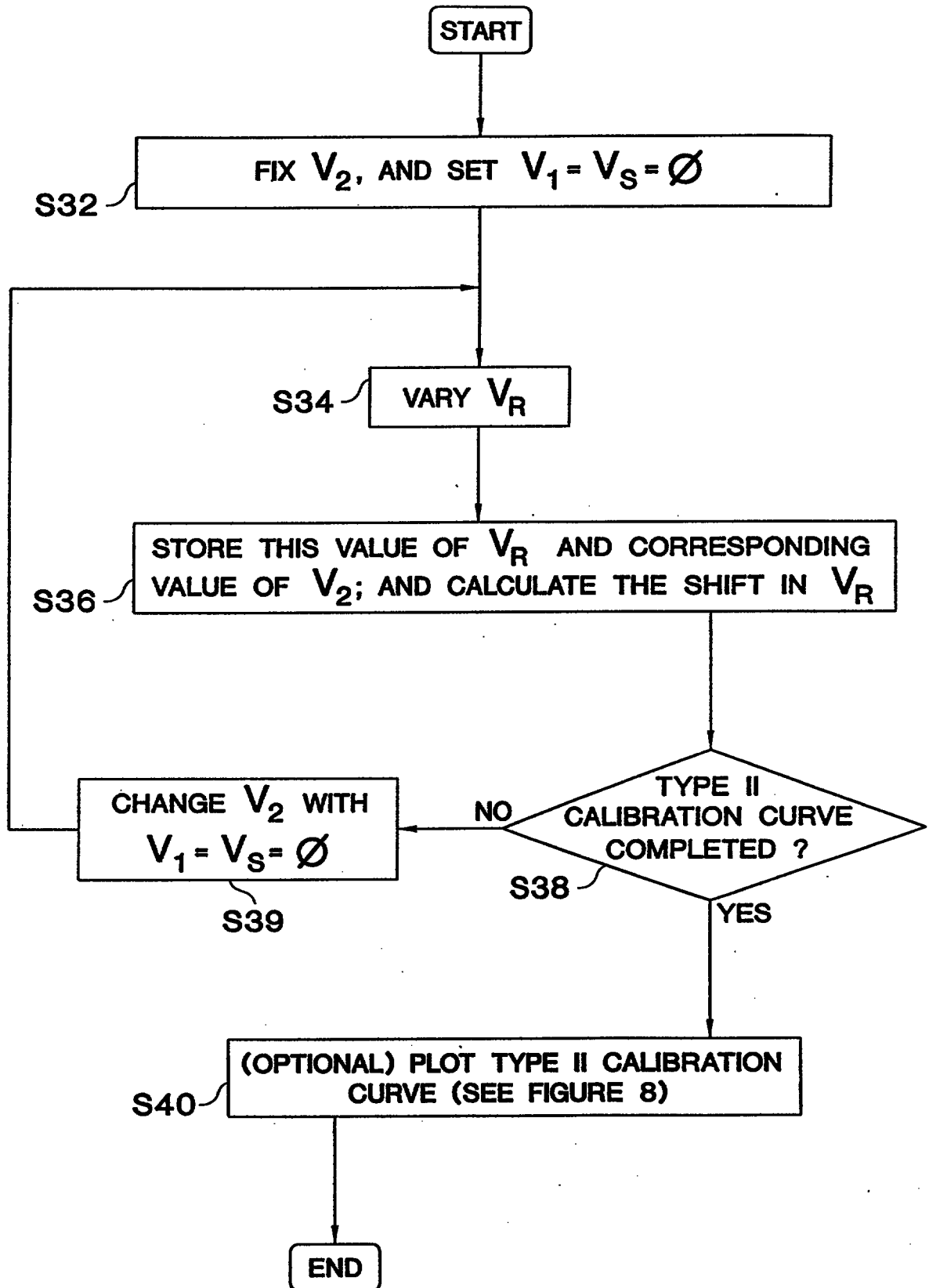
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FIG.2



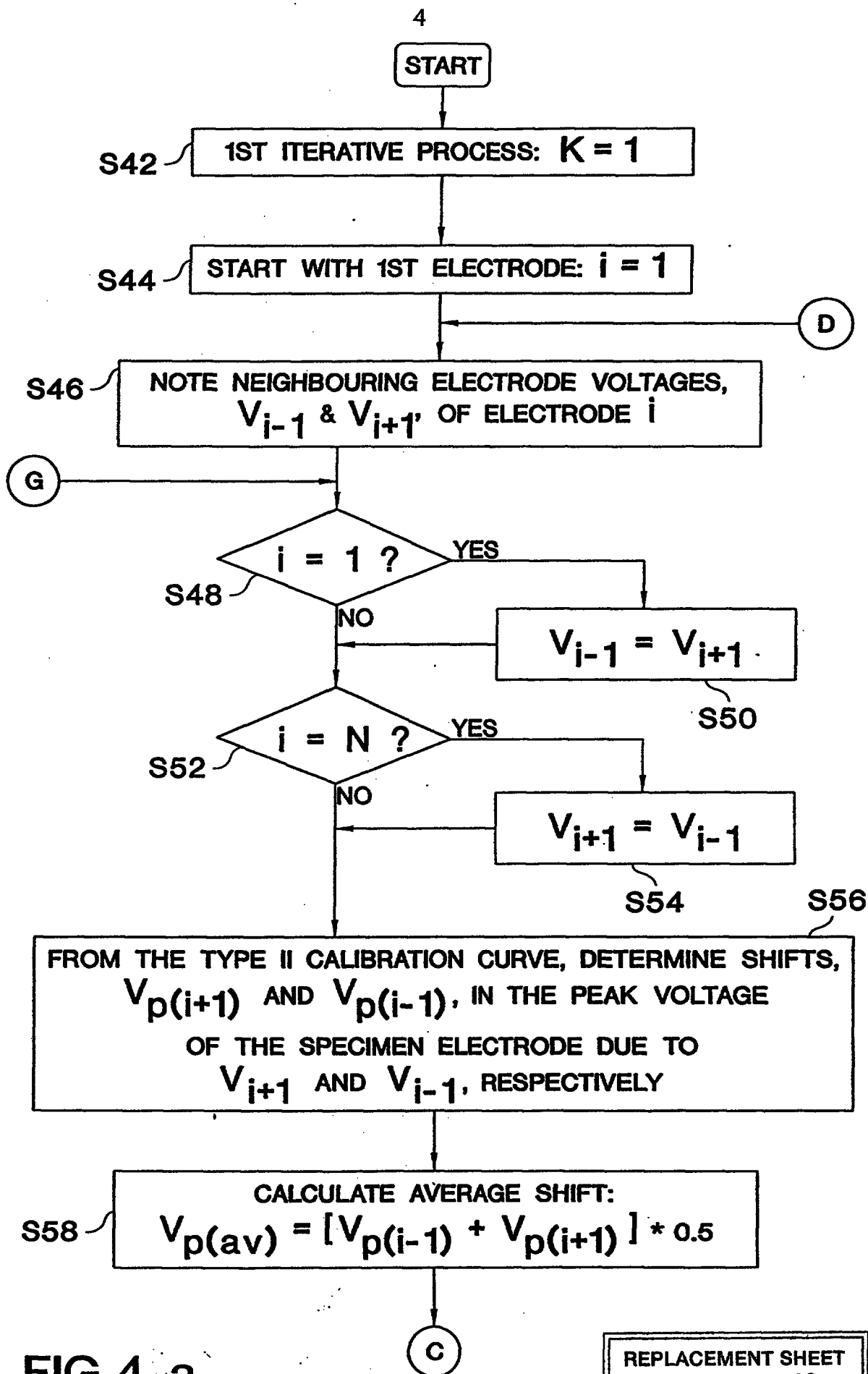


FIG.4-a

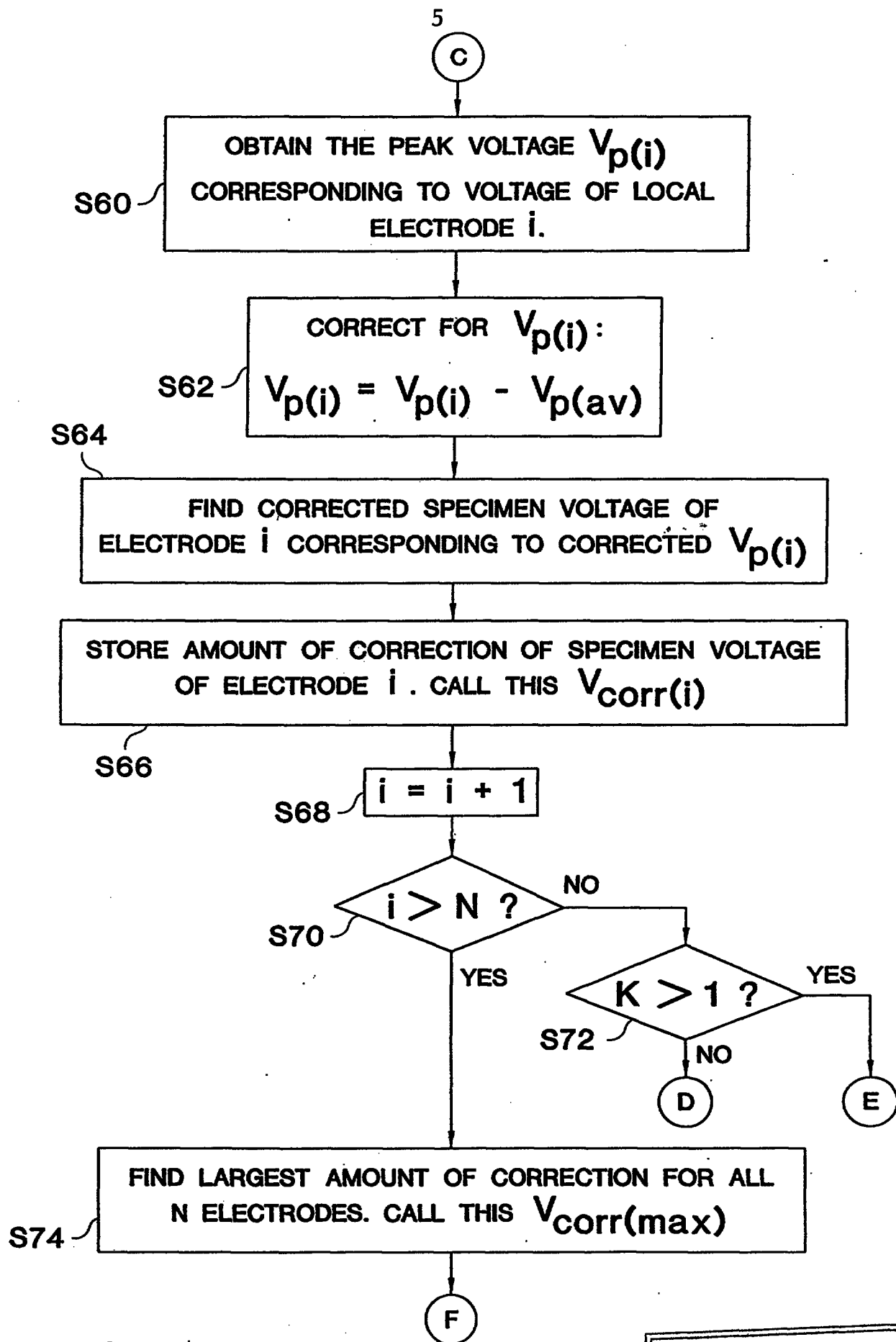


FIG.4-b

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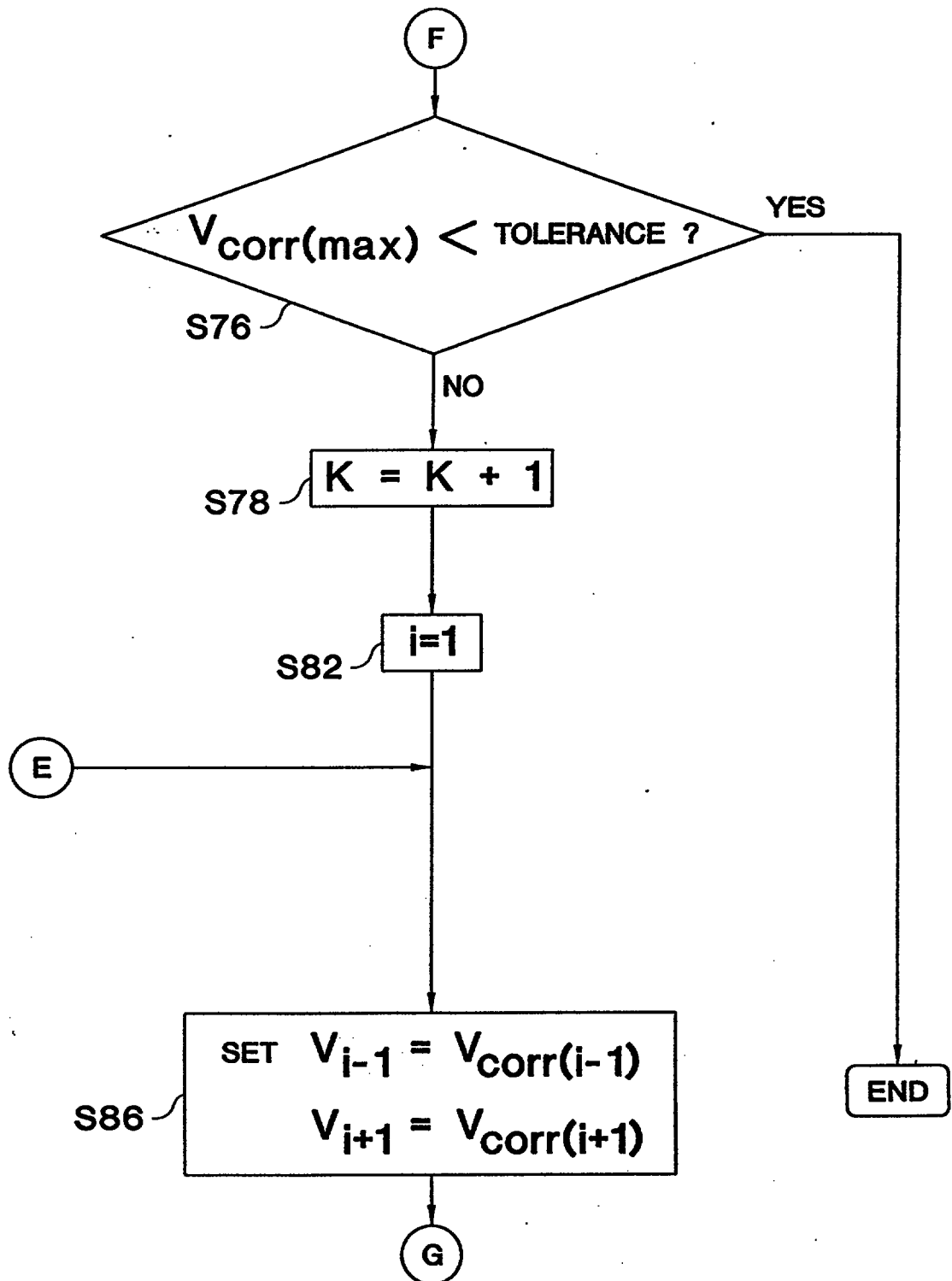


FIG.4-c

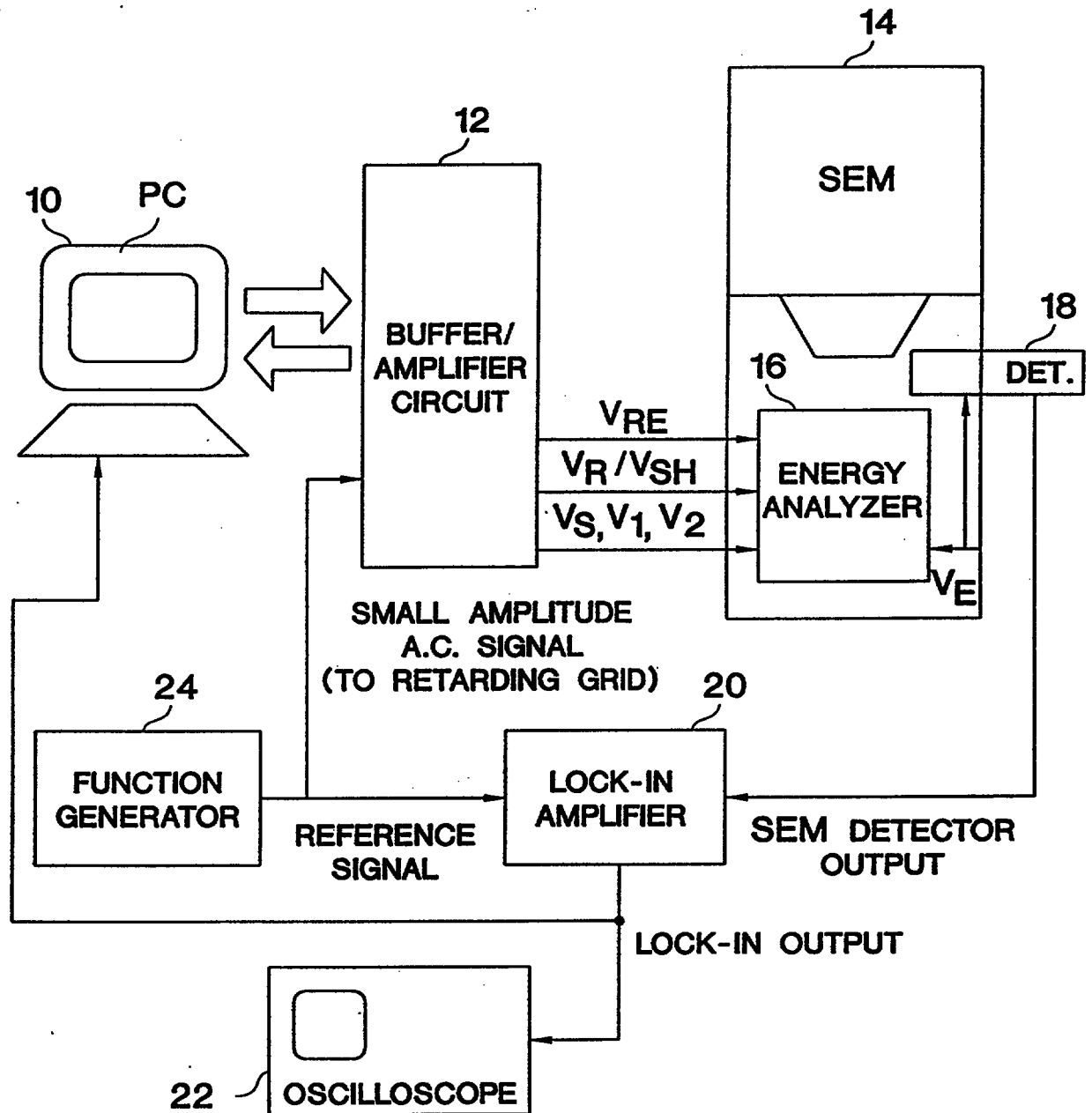
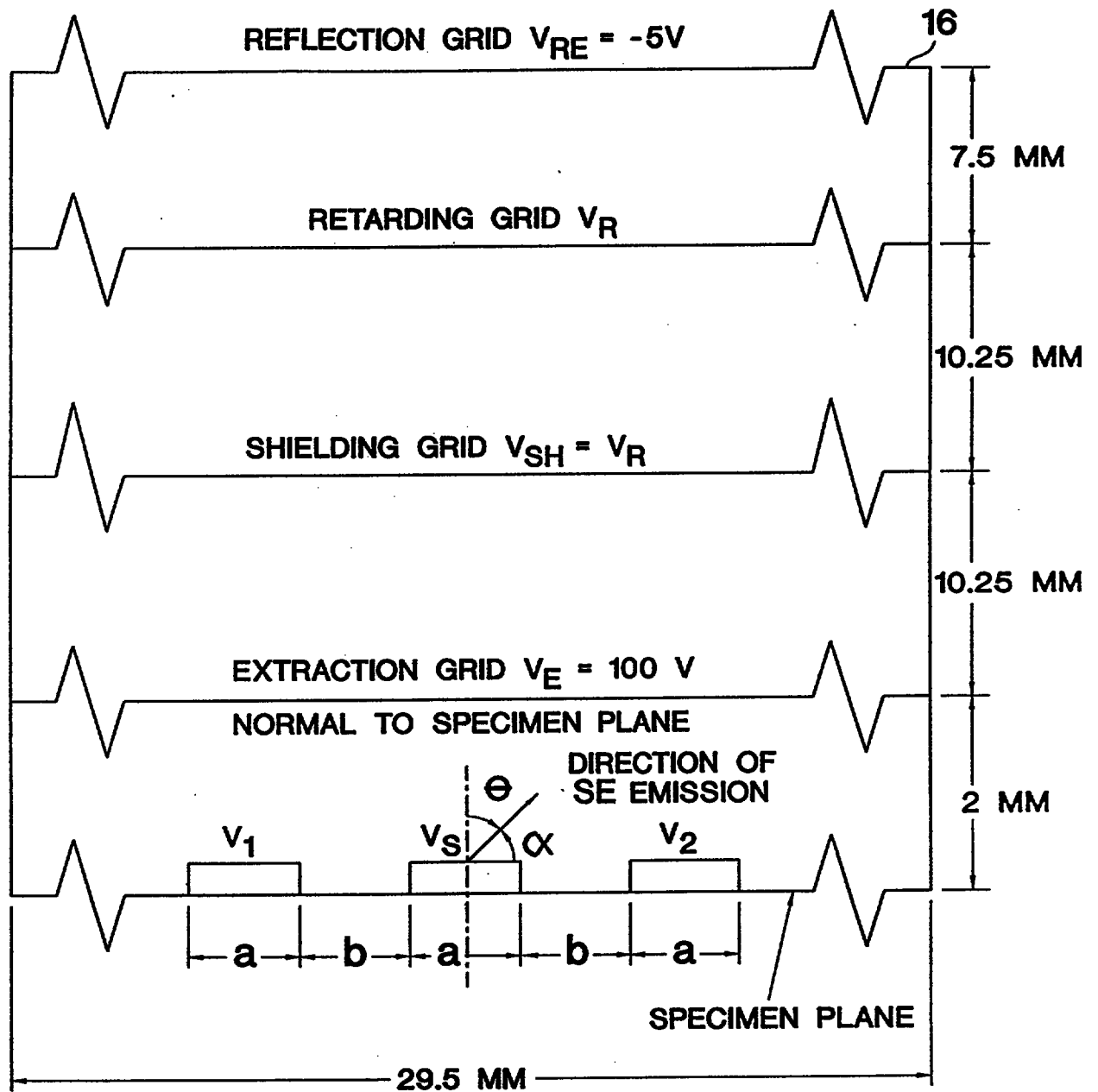


FIG. 5

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a = ELECTRODE WIDTH
b = SEPARATION BETWEEN ELECTRODES

FIG. 6

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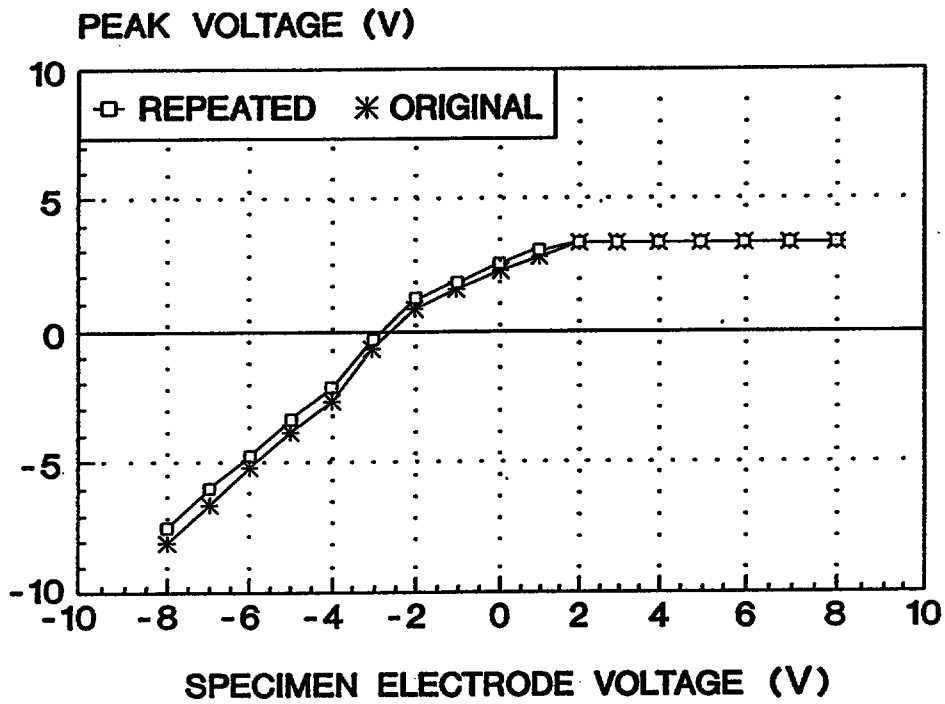


FIG. 7

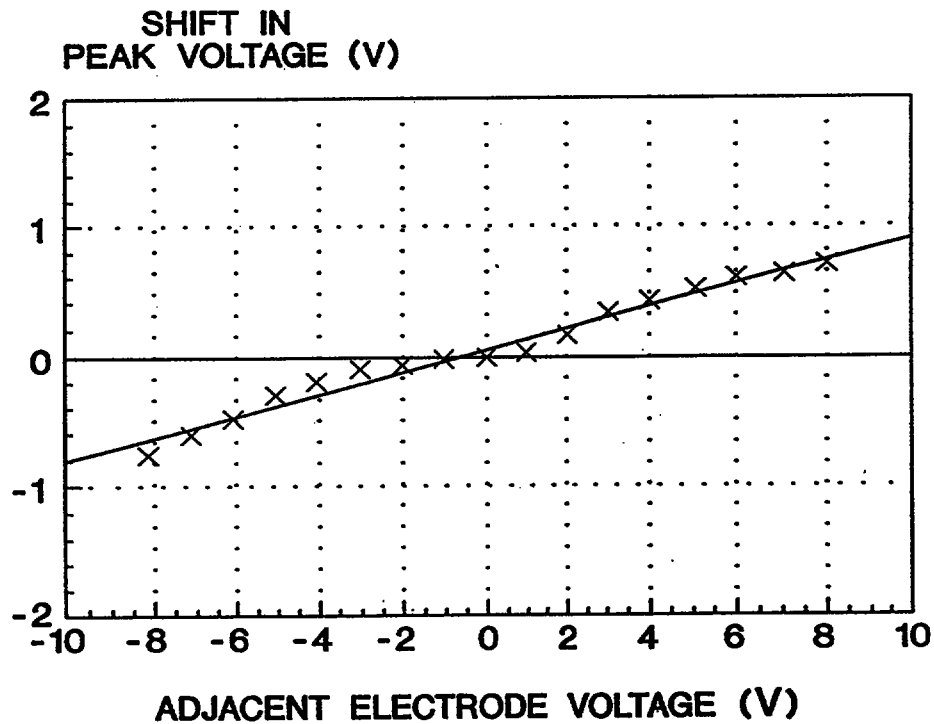


FIG. 8

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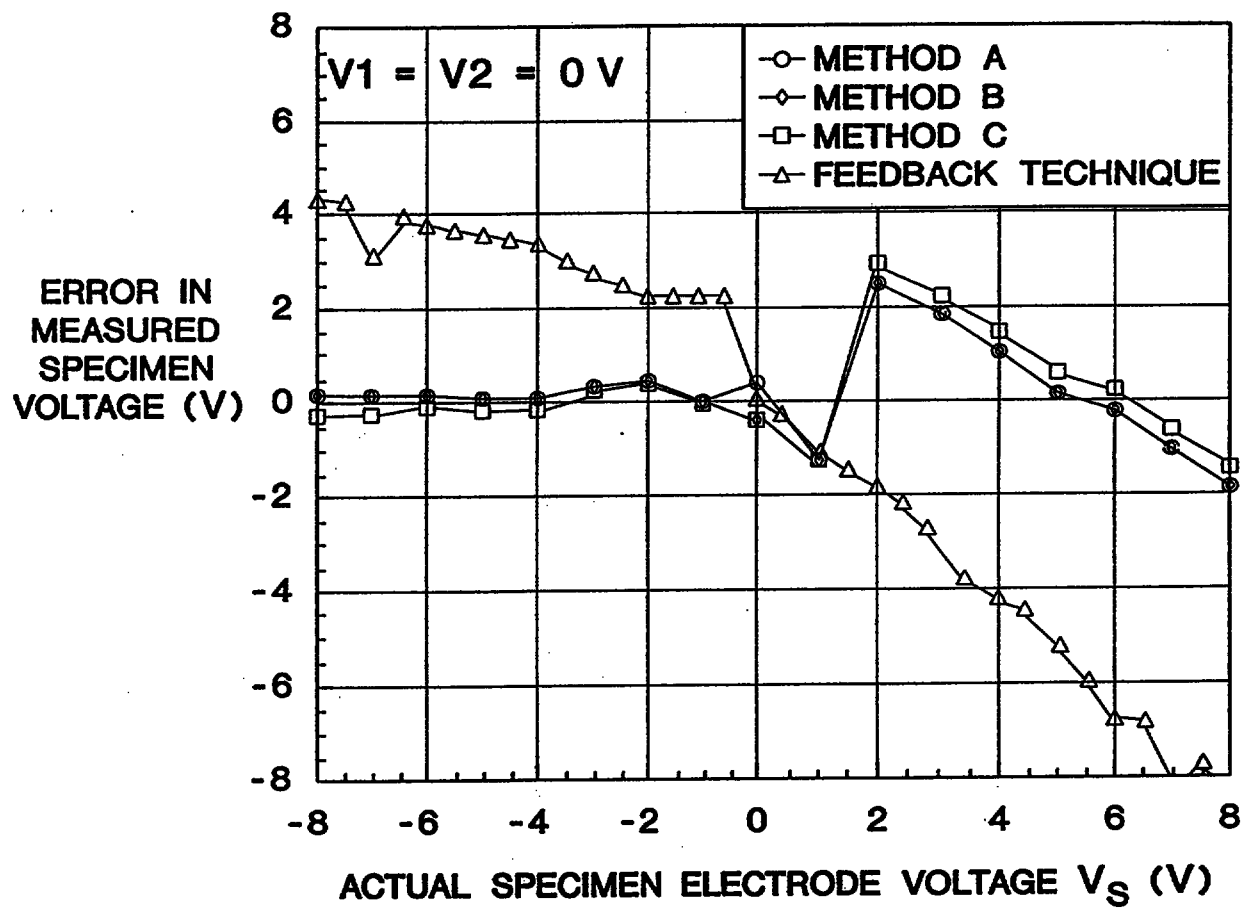


FIG. 9

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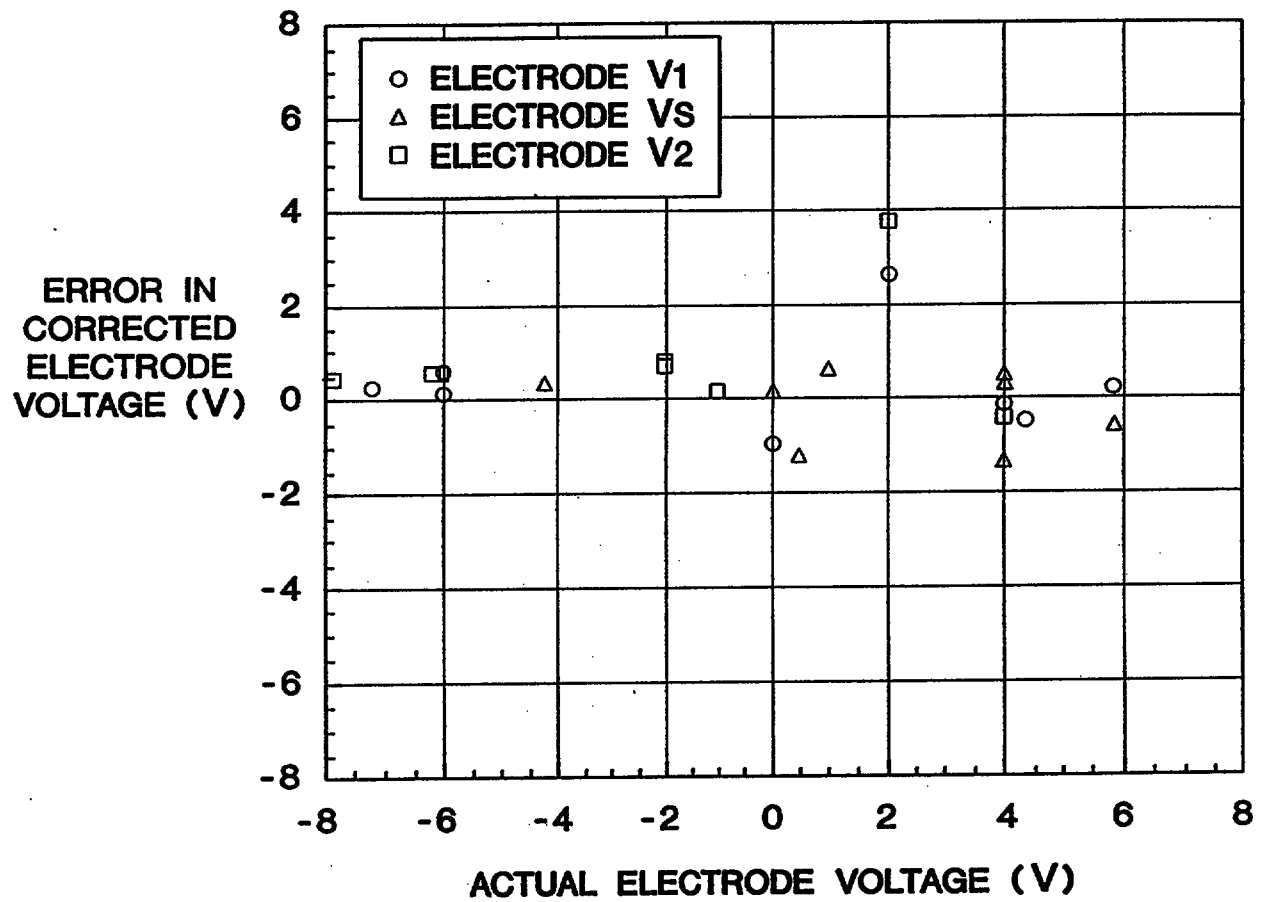


FIG. 10

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ABSTRACT

**METHOD AND APPARATUS FOR MEASURING QUANTITATIVE
VOLTAGE CONTRAST**

A method and apparatus for measuring quantitative voltage contrast are described in which an electron beam of the scanning electron microscope is located on a specimen electrode, and a grid voltage of an energy analyzer of the scanning electron microscope is varied. A detector detects secondary electron emission from the specimen electrode. A measured peak voltage of the specimen electrode is determined based on output from the detector. A specimen electrode voltage corrected for type I local field effect error is then obtained using the measured peak voltage and a type I calibration curve. The type I calibration curve represents peak voltage versus specimen electrode voltage. Type II local field effect error in the specimen electrode voltage is then corrected based on a type II calibration curve. The type II calibration curve represents a shift in specimen electrode peak voltage versus adjacent electrode voltage. (Fig. 1 is to be published.)

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