



SRDL PROCESS TECHNOLOGY LABORATORY

TECHNICAL REPORT #78

A COMPUTER-CONTROLLED CV
CHARACTERIZATION SYSTEM

Author: GLENN SHIRLEY

Date: Oct '82

Approved: Carl Aspin
Carl Aspin

Approved: L. David Sikes
L. David Sikes

Approved: Jim Smith
Jim Smith

1. INTRODUCTION

Capacitance-voltage (CV) measurements are widely used to characterize dielectric thin films and their interfaces with semiconductors. These applications range from routine monitoring of thermal gate oxides in MOS processing to fundamental academic studies. In an industrial R & D environment there is an intermediate emphasis which is process development. The development of VLSI processes, in particular, requires CV (and other) measurement support which must satisfy requirements different from both routine monitoring and academic studies. In process development, the variety of dielectric materials and applications requires considerable flexibility in the choice of measurement parameters. For example, the thin film electrical characterization lab handles dielectrics ranging from thermal SiO₂ through CVD and PECVD SiO₂ and Si₃N₄ to polyimides. Another requirement is the increasing sophistication of measurements required to monitor VLSI process development. All process development has a third requirement which tends to run counter to flexibility and sophistication, and that is throughput. On the other hand, process development monitoring measurements seldom require new fundamental knowledge. The central problem is to tailor existing techniques described in the literature to the process development environment.

A conventional approach to research CV characterization involves the use of a lock-in amplifier, a ramp generator, a signal generator, an X-Y plotter, a thermal chuck, etc., synchronized by TTL triggers, etc. The various parameters would be set by the operator using the front-panel dials and switches. This is adequate in an academic setting, but for industrial process development the requirement of throughput makes this analog approach tedious and difficult to reproduce because of the detailed attention which must be paid to parameter settings. In practice, the analog approach forces a choice between flexibility and throughput.

Since the mid-1970's when the General-Purpose Interface Bus* (GPIB) came into common use, and especially since 1979 when Hewlett-Packard intro-

* Also known as the IEEE-488 bus or, according to Hewlett-Packard, as the Hewlett-Packard Interface Bus (HPIB).

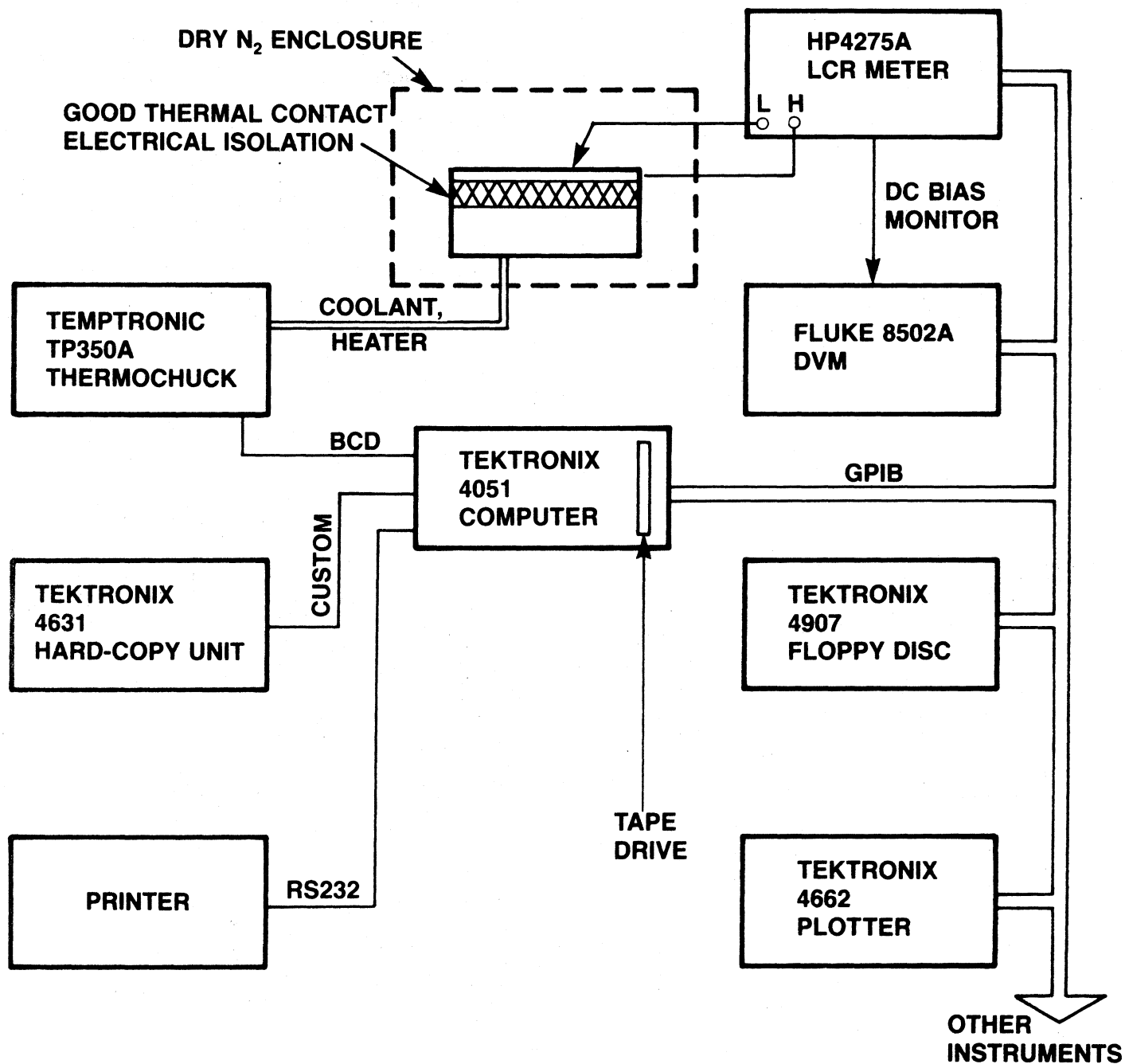


FIGURE 1. THE HARDWARE CONFIGURATION

duced the HP4275A LCR Meter, it has become possible conveniently to build a computer-controlled digital system which overcomes the problems of analog systems, and which affords significant additional advantages. The GPIB has made it trivial to define the hardware aspect of a system because computer and instruments are plug-compatible, and instruments can be configured either by front-panel settings or from the computer via the GPIB. Readings taken by the instruments can also be transmitted to the computer over the GPIB. Most of the labor in developing a GPIB-based system is in software development.

This report describes the computer-controlled digital CV system designed and built in the Thin Film Section of PTL. The discussion is intended to describe the capabilities of the system, and to indicate what is required to duplicate the system in another lab. Detailed software descriptions and lists are available from the author and will not be given here. The system described in this report is a self-contained subset of a larger system, other aspects of which will be covered in subsequent reports.

2. THE HARDWARE SYSTEM

Although interconnection of the elements of the hardware system is easy, choice of the elements themselves involves some non-trivial considerations.

A basic choice is the computer used to control the system. We chose the Tektronix 4051 Graphics System because it has graphics capability permitting visual interaction with the data. This frees the user to think on a higher plane of abstraction. Another essential is that the computer be easily programmable in a high level language, eg. BASIC, including communication with peripherals with simple input/output commands. The display peripherals include a 1200 baud* matrix printer, a plotter, and a hard copy unit. The hard copy unit gives copies of the 4051 screen and serves as a backup to the printer and plotter, as well as providing copies of unusual display conditions. The computer has a built-in tape drive which is used only for scratch and backup applications. The main data storage facility is the Tektronix 4907 dual floppy disc system. This allows one to develop

* A slower printer causes inconvenient delays.

sophisticated software systems with interacting files and libraries of files, both data files and program files. The software system described in the next section requires the disc drive as a part of the system. Our system has a dual drive since this permits separation of programs and data, and it simplifies backup procedures. The software system requires a real-time clock that can be read from an executing program, and we use the clock built into the disc drive system.

Instrumentation includes the Hewlett-Packard HP4275A LCR meter, a digital voltmeter and a digitally controlled thermochuck. All the parameters for these instruments can be set up under program control through digital interfaces without operator intervention. Readings are also transmitted through these interfaces. The HP4275A LCR meter can measure capacitance, C, and parallel conductance, G, (or any other representation of the impedance) at 10 discrete frequencies from 10KHz to 10MHz in 1-2-4 steps at any bias in the range $-99.9V \leq V \text{ bias} \leq 99.9V$. The actual bias seen by the sample is monitored by a digital voltmeter. The temperature of the sample is controlled by a Temptronic TP350A thermochuck. This controls at any temperature in the range -30°C to 200°C . The setpoint and current temperature is communicated through a separate BCD interface (Trans-Era 632-BCD). All of the equipment is protected from line power fluctuations by an isolation transformer.

Except for the Temptronic TP350A, the hardware has been trouble-free. Problems with the Temptronic unit include inadequate AC isolation from ground, and condensation on the refrigeration evaporator even when controlling at room temperature. The latter is easily solved by enclosing the chuck in a nitrogen atmosphere, but the former is fundamental to the design.* Recently the Micromanipulator Co. has introduced their HS-4320 which, hopefully, will solve some of these problems, and which, moreover, is controllable via the GPIB.

The hardware configuration is summarized in Figure 1.

3. THE SOFTWARE SYSTEM

The software system, diagrammed in Fig. 2, resides on discs. The system is divided into a data acquisition section and a data analysis section.

* A detailed analysis of this problem is available from the author.

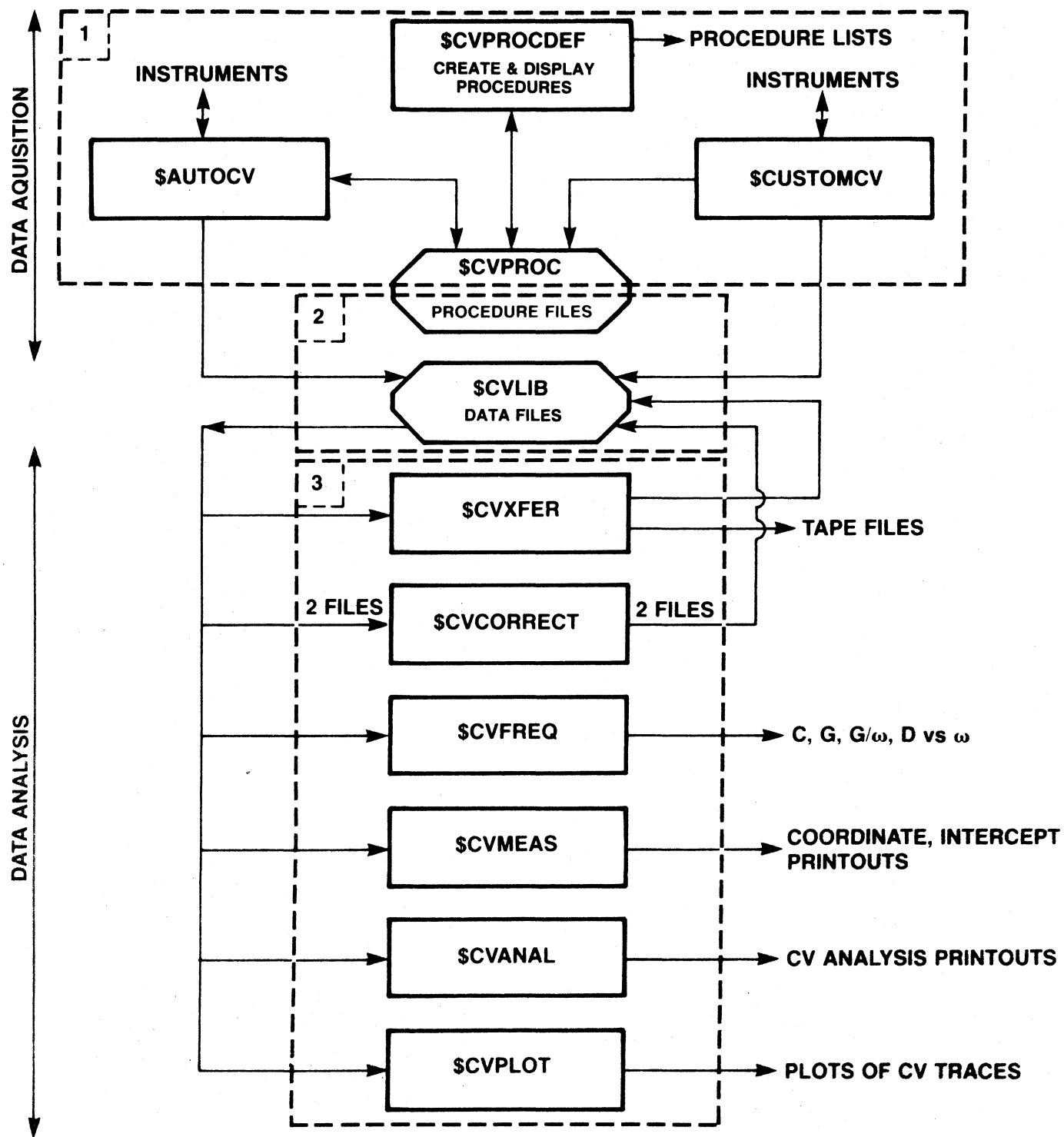


FIGURE 2. THE SOFTWARE SYSTEM.

1. DATA ACQUISITION PROGRAM DISC,
2. USER DATA DISC
3. DATA ANALYSIS PROGRAM DISC.

The two sections communicate via disc data files written under a user-defined name into the library %CVLIB. The discussion of the two sections will be separate, and we will follow several specific examples through various stages of data acquisition and analysis, returning to examples at appropriate points in the discussion.

3.1 DATA ACQUISITION

This function is implemented with three programs, %CVPROCDEF, %CUSTOMCV, and %AUTOCV and a library of data files named %CVPROC.

CV measurements involve a sequence of temperature-bias stresses and C-V (and G-V) traces which we shall call a procedure. This sequence may be as simple as the standard Na⁺-shift monitoring procedure used for process monitoring, or it can be quite complicated. A feature of our software system is that one can enter, display and edit a CV procedure using %CVPROCDEF before making any measurements. The procedure so defined is then saved in the library %CVPROC under a user-defined name where it is available to be called up and executed by the program %AUTOCV. It is %AUTOCV which controls instruments and handles the real-time data acquisition. There are three basic types of steps which may be sequenced in any way using %CVPROCDEF, and each type of step has several parameters to be defined:

(a) Trace (Parameters: Vstart, Vstop, R, F, T). This causes C and G to be measured, displayed on a real-time plot and stored in memory at values of bias starting from Vstart and ending at Vstop with a ramp rate of R (volts/sec) at a frequency of F(Hz) and temperature T (°C). The trace begins when the temperature reaches T after changing from its previous value.

(b) Ramp (Parameters: Vstart, Vstop, R, T). This is the same as the trace option except that measurements of C and G are not made, plotted or stored. The ramp step allows gradual voltage transitions rather than abrupt transitions between procedure steps, if desired.

(c) Soak (Parameters: time, T, Vbias). This step immediately applies the specified voltage bias, Vbias, and starts heating or cooling to the specified temperature, T. When T is reached, the clock starts and holds the temperature for the specified time. At the end of the time the chuck heats or cools to the temperature of the next step in the procedure under bias, Vbias. To apply bias just while the sample is at the requested temperature, one can use "dummy" soak steps as shown in Example 5 below.

The parameters in the procedure steps can have value within the range of the measurement equipment:

$$-99.9V \leq V_{start}, V_{stop}, V_{bias} \leq 99.9V$$

$$F = 10KHz - 10MHz \text{ in } 1-2-4 \text{ steps}$$

$$-30^{\circ}C \leq T \leq 200^{\circ}C$$

$$\text{time} \geq 1 \text{ sec}$$

R (ramp rate) can have any value (Volts/sec)

In principle, the ramp rate R can have any value, but the bias voltage is changed in discrete steps which for large ramp rates can be large because of the finite (~ 1.5 sec) cycle time between measurements. For sufficiently slow ramp rates (not using the limiting cycle time), 100 points are plotted and stored per trace.

Once a procedure has been defined by %CVPROCDEF and stored in %CVPROC, it can be recalled and executed any number of times by %AUTOCV. Thus, even quite complicated procedures can be exactly reproduced with minimal operator intervention. Examples will illustrate the system's flexibility and the wide variety of questions which can be addressed.

Example 1. Standard CV qualification. The procedure shown in Figure 3a, named STDCV, is a standard MOS gate oxide qualification procedure. When this procedure was executed by %AUTOCV, the data was stored on a file PEMASK1 in the library %CVLIB. Later, this data was recalled and plotted using the program %CVPLOT, yielding the plot in Figure 3b. Before executing a procedure in %AUTOCV the operator enters a string of characters which appears in the heading of every plot generated from the data file in %CVLIB. The computer automatically appends to this string the name of the procedure in

*** CV PROCEDURE DEFINITION ***

Old Procedure Name: STDCV

Step# 1 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 2 (Trace) Ustart= 5.00 Ustop= -5.00 R= 0.10 (V/s)
Freq= 1.0E+006 (Hz) T= 25.0 (deg C)

Step# 3 (Soak) Time = 300 (sec) Temp= 200.0 (deg C) Bias= 20.00

Step# 4 (Trace) Ustart= 5.00 Ustop= -5.00 R= 0.10 (V/s)
Freq= 1.0E+006 (Hz) T= 25.0 (deg C)

Step# 5 (Soak) Time = 300 (sec) Temp= 200.0 (deg C) Bias= -20.00

Step# 6 (Trace) Ustart= 5.00 Ustop= -5.00 R= 0.10 (V/s)
Freq= 1.0E+006 (Hz) T= 25.0 (deg C)

Hit RETURN to continue...

FIGURE 3A. STANDARD MOS QUALIFICATION PROCEDURE.

CV QUAL. PE-17-03-81-2 MASK 1 STDCV 18-MAR-81 08:41:52 (PEMASK1)

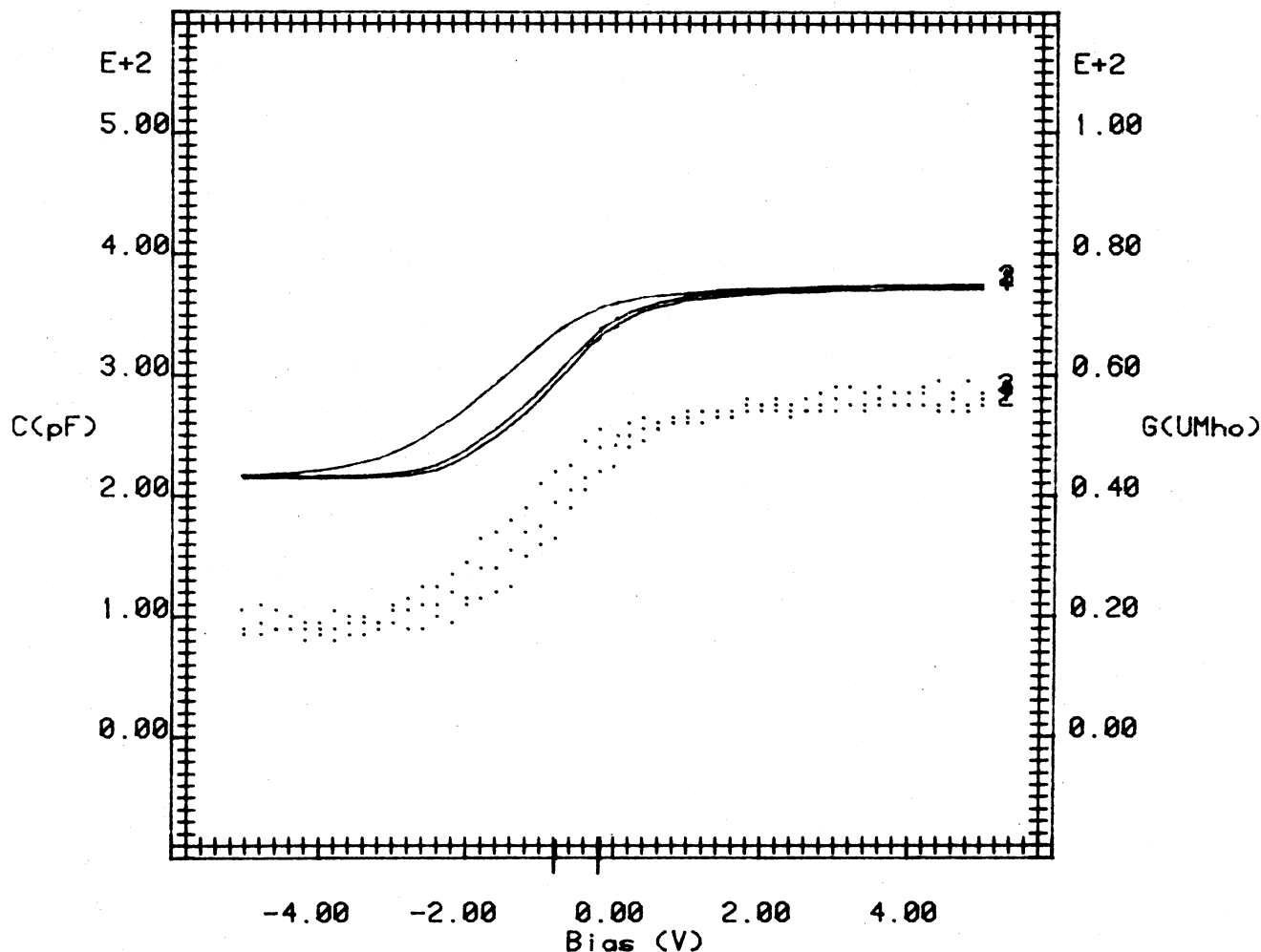


FIGURE 3B.
PLOT GENERATED BY THERMAL SiO₂ USING PROCEDURE IN FIGURE 3A.
C: SOLID LINES, G: DOTTED LINES.

*** CV PROEEDURE DEFINITION ***

Old Procedure Name: HYST100MID

Step# 1 (Trace) Ustart= 0.00 Ustop= -99.90 R= 1.00 (V/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)

Step# 2 (Soak) Time = 100 (sec) Temp= 25.0 (deg C) Bias= -99.90

Step# 3 (Trace) Ustart= -99.90 Ustop= 99.90 R= 1.00 (V/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)

Step# 4 (Soak) Time = 100 (sec) Temp= 25.0 (deg C) Bias= 99.90

Step# 5 (Trace) Ustart= 99.90 Ustop= 0.00 R= 1.00 (V/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)

Hit RETURN to continue...

FIGURE 4A.
HYSTERESIS PROCEDURE.

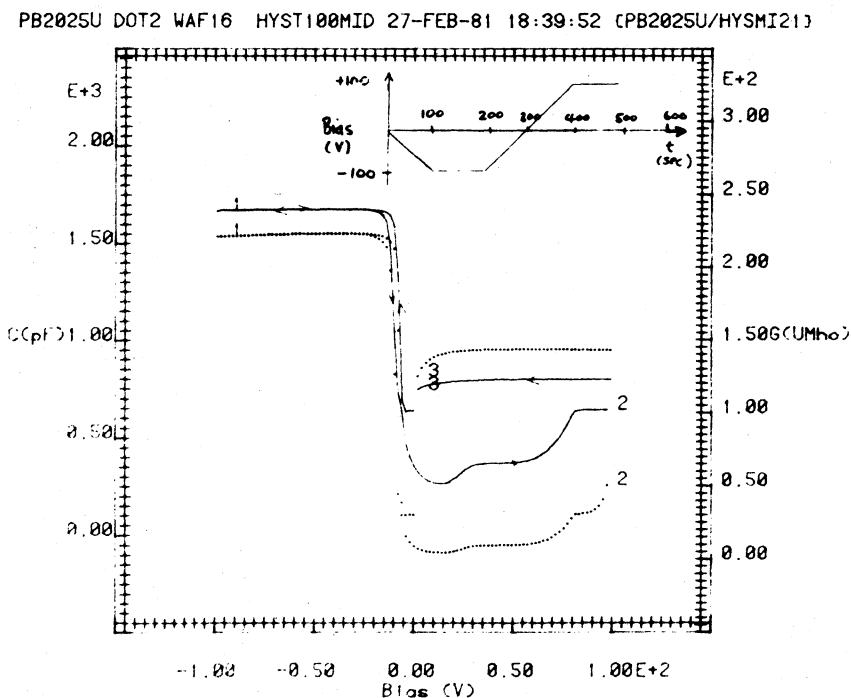


FIGURE 4B.

**HYSTERESIS TRACES SHOWING CHARGE INJECTION GENERATED FROM
PROCEDURE IN FIGURE 4A. PLASMA-ENHANCED CVD SiO₂.**

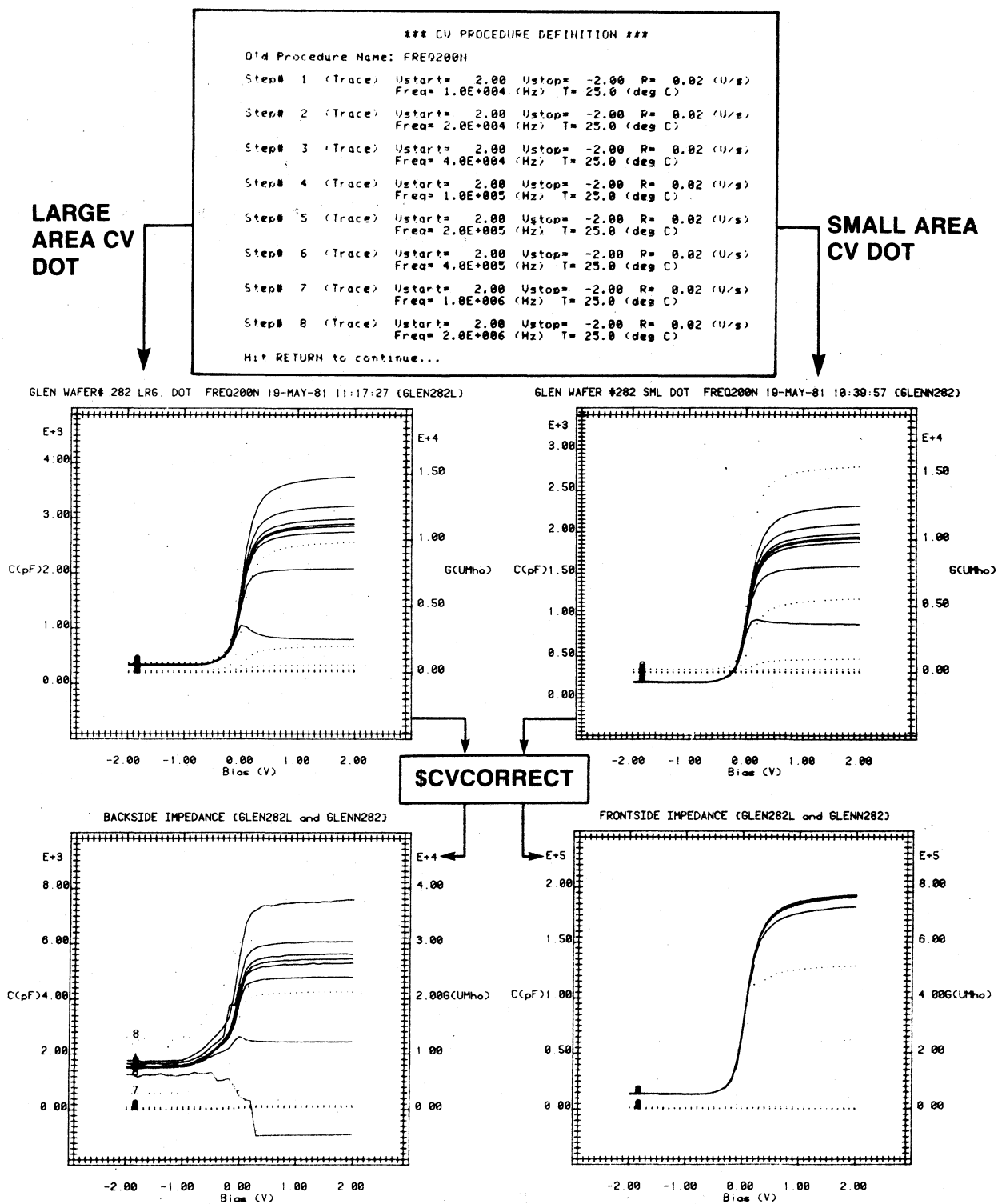


FIGURE 5.

TOP: FREQUENCY SERIES PROCEDURE. MIDDLE: TRACES GENERATED ON SMALL AND LARGE DOTS. BOTTOM: OUTPUT OF \$SCVCORRECT. THERMAL SiO₂.

%CVPROC which generated the plot, the date and time and the name of the data file in %CVLIB on which the data is stored. Thus the system is self-documenting as far as is practical.

Example 2. Hysteresis study of plasma-enhanced CVD SiO₂. A commonly-used type of procedure is shown in Figure 4a. This subjected the sample to the bias-time profile shown as the inset in Figure 4b, and generated the traces shown in the main part of the figure. The sense of the hysteresis shows that charge injection is occurring in this sample. The finished plot does not show the sense of the hysteresis, but the plot generated by %CVPLOT reproduces the original traces in the correct temporal sequence, so direction arrows may be determined by watching the plot as it is reproduced.

Example 3. Frequency study of thin thermal (gate) SiO₂. The frequency variation of CV plots is not usually done using conventional CV equipment, but with our equipment it is just as easy to set up a frequency series as any other procedure. The procedure at the top of Figure 5 generated the middle traces in this figure. The bottom traces will be explained below.

The system is particularly well-suited to a class of measurements which gives flat-band voltage shifts as functions of (a) temperature at fixed bias and time of stress, (b) time of stress at fixed temperature and bias, or (c) bias at fixed time of stress and temperature. These measurements give, respectively, (a) activation energies, (b) kinetic laws, or (c) stress activation laws for charge movement in, or injection into, dielectric films. Procedures for this type of measurement can be quite complicated and nearly impossible to carry out manually without error, let alone reproduce accurately with different samples. We present examples of measurements of type (a) and (b).

Example 4. Activation energy for charge injection into plasma-enhanced CVD SiO₂. The procedure in Figure 6 has standard room-temperature traces interleaved with soaks at increasing temperatures chosen for equal intervals in 1/T, with bias and time of stress held constant. The traces generated when this procedure is executed by %AUTOCV are also shown in Figure 6. The separation between successive traces increases with temperature. This data will be analysed further below.

*** CU PROCEDURE DEFINITION ***

Old Procedure Name: ACTIV25

```

Step# 1 (Trace)  Ustart= -25.00  Ustop=  15.00  R=  0.50 (V/s)
                  Freq= 1.0E+004 (Hz)  T= 25.0 (deg C)

Step# 2 (Soak)   Time = 100 (sec)  Temp=  25.0 (deg C)  Bias= -40.00

Step# 3 (Trace)  Ustart= -25.00  Ustop=  15.00  R=  0.50 (V/s)
                  Freq= 1.0E+004 (Hz)  T= 25.0 (deg C)

Step# 4 (Soak)   Time = 100 (sec)  Temp=  55.0 (deg C)  Bias= -40.00

Step# 5 (Trace)  Ustart= -25.00  Ustop=  15.00  R=  0.50 (V/s)
                  Freq= 1.0E+004 (Hz)  T= 25.0 (deg C)

Step# 6 (Soak)   Time = 100 (sec)  Temp=  95.0 (deg C)  Bias= -40.00

Step# 7 (Trace)  Ustart= -25.00  Ustop=  15.00  R=  0.50 (V/s)
                  Freq= 1.0E+004 (Hz)  T= 25.0 (deg C)

Step# 8 (Soak)   Time = 100 (sec)  Temp= 140.0 (deg C)  Bias= -40.00

Step# 9 (Trace)  Ustart= -25.00  Ustop=  15.00  R=  0.50 (V/s)
                  Freq= 1.0E+004 (Hz)  T= 25.0 (deg C)

Step# 10 (Soak)  Time = 100 (sec)  Temp= 200.0 (deg C)  Bias= -40.00

Step# 11 (Trace) Ustart= -25.00  Ustop=  15.00  R=  0.50 (V/s)
                  Freq= 1.0E+004 (Hz)  T= 25.0 (deg C)

```

Hit RETURN to continue...

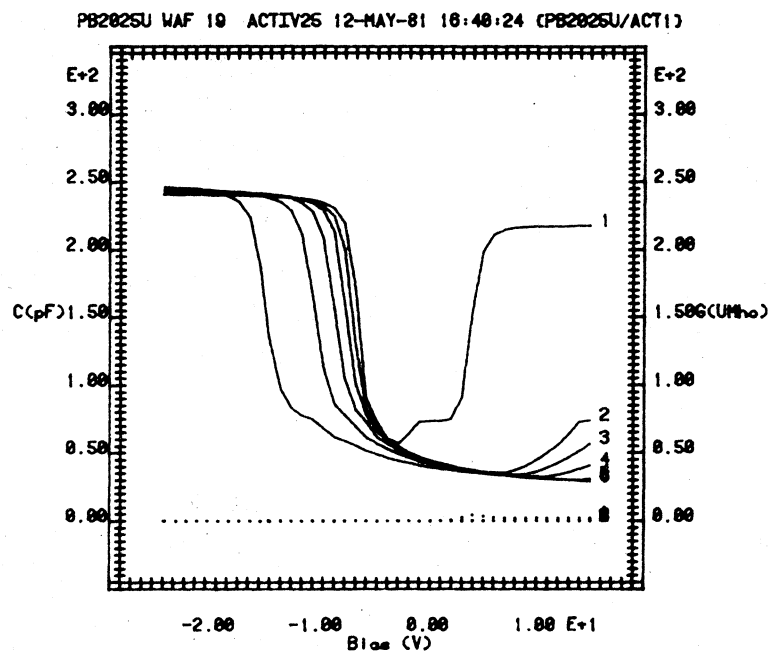


FIGURE 6.

TOP: PROCEDURE TO DETERMINE ACTIVATION ENERGIES. BOTTOM: TRACES GENERATED BY THIS PROCEDURE. PLASMA-ENHANCED CVD SiO_2 .

*** CU PROCEDURE DEFINITION ***

Old Procedure Name: GAYSHIFT

```

Step# 1 (Trace) Ustart=100.00 Ustop=-100.00 R= 1.00 (U/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)

Step# 2 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 3 (Soak) Time = 60 (sec) Temp= 200.0 (deg C) Bias= -5.00

Step# 4 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 5 (Trace) Ustart=100.00 Ustop=-100.00 R= 1.00 (U/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)

Step# 6 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 7 (Soak) Time = 300 (sec) Temp= 200.0 (deg C) Bias= -5.00

Step# 8 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 9 (Trace) Ustart=100.00 Ustop=-100.00 R= 1.00 (U/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)

Step# 10 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 11 (Soak) Time = 900 (sec) Temp= 200.0 (deg C) Bias= -5.00

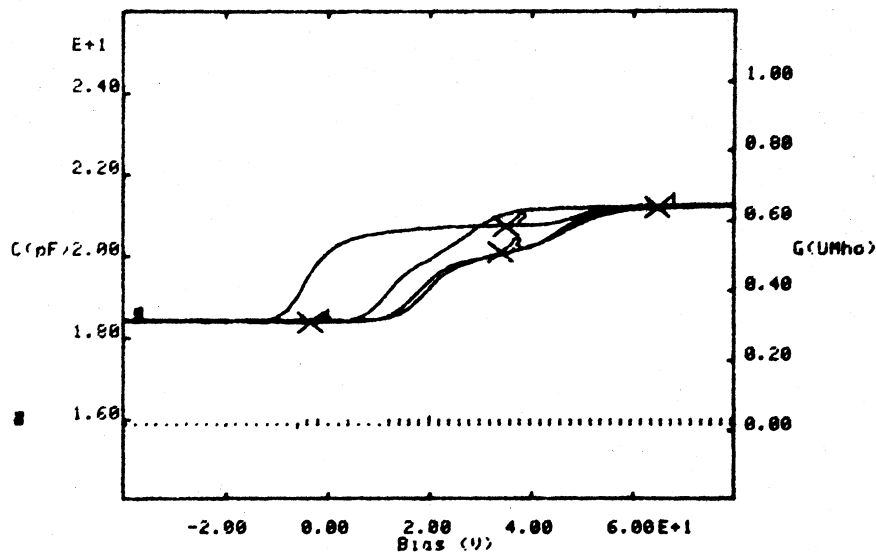
Step# 12 (Soak) Time = 1 (sec) Temp= 200.0 (deg C) Bias= 0.00

Step# 13 (Trace) Ustart=100.00 Ustop=-100.00 R= 1.00 (U/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)
    
```

Hit RETURN to continue...

Position, Intercepts, Replot (P/I/R/P)
Position pointer & hit "RETURN" (S to stop)

GAY S. WAFER # 14 DOT(2,0) GAYSHIFT 09-JUL-81 11:36:40 (GAYS14)



>> CURSOR POSITIONS <<

Position	Bias (V)	Cap (pF)	G (uMho)
1	64.85	21.20	6.40E-001
2	34.99	20.74	5.86E-001
3	33.96	20.10	5.12E-001
4	-3.41	18.39	3.12E-001

Hit "RETURN" to continue (screen will clear)

FIGURE 7.

KINETICS STUDY OF POLYIMIDE. TOP: PROCEDURE WITH DUMMY SOAKS.
MIDDLE: CURVES GENERATED BY PROCEDURE SHOWING CURSOR
POSITIONS. BOTTOM: CURSOR COORDINATES.

Example 5. Polarization kinetics of polyimide. The procedure in Figure 7 was run on a composite film with $1.4\ \mu$ of polyimide on $1000\ \text{\AA}$ of thermal SiO_2 . This procedure has standard room-temperature traces interlaced with soaks for increasing times at fixed bias and temperature. The "dummy" one second soaks are used to turn the bias on only when the stress temperature is reached, and to turn it off at the end of the stress period just before cooling to the trace temperature commences. The data generated by this procedure is shown in Figure 7.

Sometimes, with completely unknown samples, it is useful to do a "seat-of-pants" measurement; that is, to execute a soak or trace, observe the result, and then decide on the next step. This can be useful, for example, if one is not sure whether the flat-band voltage falls within the trace voltage span chosen. The program %CUSTOMCV allows the operator to perform this type of measurement. Shown in Figure 8 are screen images for a data acquisition session. The screen was cleared midway through the session to make room for further interrogation and plots, but the earlier data was not lost. The program has two options, both exercised during the sample session: (a) the sequence of steps chosen by the operator can be stored in the procedure library, %CVPROC, as they are executed, under a user-defined name, (b) the data accumulated can be saved in the data library %CVLIB for later analysis using data analysis programs. Saving the procedure serves two purposes; first, a complete and detailed record of the sample's history is available for display using the printout function of the program %CVPROCDEF, and second, the procedure is available for execution in the usual fashion by %AUTO CV. Thus, a procedure developed "manually" under %CUSTOMCV may be repeated automatically any number of times with minimal operator intervention. Displays generated from the saved procedure and plot data are shown in Figure 9.

3.2 DATA ANALYSIS

All data generated by the data acquisition part of the software system is written to data files in the library %CVLIB in a standard format. In addition to the C-V and G-V trace data, these files contain capacitor area and frequency data as well as an identifying string which contains date, time, generating procedure name, data file name and user-supplied

*** CUSTOM CV PLOTTING ***

Is chuck H1 or L0 (H/L)H

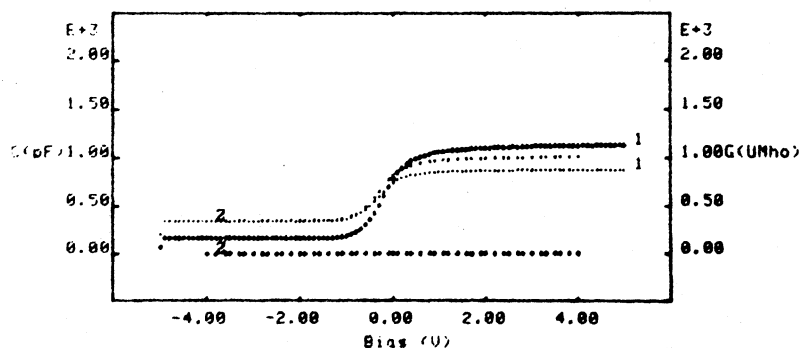
Enter plot caption and hit "RETURN" to continue
STANDARD MOS SIO2

Dot area (cm²).01503

Save procedure (Y/N)Y

New procedure filenameMOS1

```
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)H
Ustart,Ustop,R,F,T
-5,5,0.05,1E6,25
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)S
Time/Temp/Bias
20,0,-2
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)P
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)S
Time/Temp/Bias
30,50,2
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)H
Ustart,Ustop,R,F,T
4,-4,0.05,1E4,25
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)S
Time/Temp/Bias
20,0,-2
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)P
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)C
```



```
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)H
Ustart,Ustop,R,F,T
5,-5,0.1,1E6,10
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)Q
Save data (Y/N)Y
FilenameMOS1
Ustart,Ustop,R,F,T
5,-5,0.1,1E6,10
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)H
Ustart,Ustop,R,F,T
5,-5,0.1,1E6,10
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)H
```

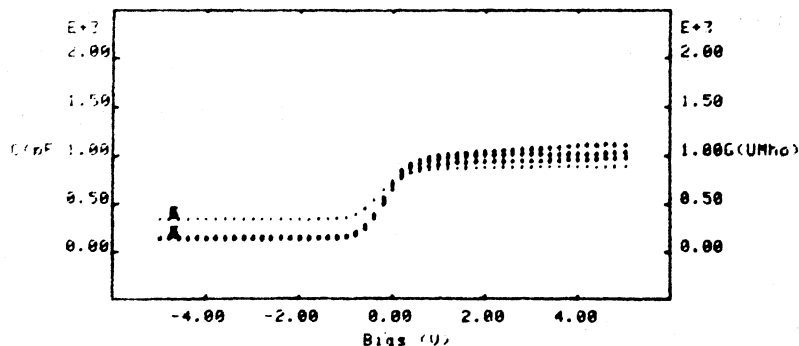


FIGURE 8.

SCREEN IMAGES FOR \$CUSTOMCV REAL-TIME DATA ACQUISITION SESSION.

*** CV PROCEDURE DEFINITION ***

Old Procedure Name: MOS1

Step# 1 (Trace) Ustart= -5.00 Ustop= 5.00 R= 0.05 (V/s)
Freq= 1.0E+006 (Hz) T= 25.0 (deg C)

Step# 2 (Soak) Time = 30 (sec) Temp= 50.0 (deg C) Bias= 2.00

Step# 3 (Trace) Ustart= 4.00 Ustop= -4.00 R= 0.08 (V/s)
Freq= 1.0E+004 (Hz) T= 25.0 (deg C)

Step# 4 (Soak) Time = 20 (sec) Temp= 0.0 (deg C) Bias= -2.00

Step# 5 (Trace) Ustart= 4.00 Ustop= -4.00 R= 0.08 (V/s)
Freq= 1.0E+004 (Hz) T= 25.0 (deg C)

Step# 6 (Trace) Ustart= 5.00 Ustop= -5.00 R= 0.10 (V/s)
Freq= 1.0E+006 (Hz) T= 0.0 (deg C)

Step# 7 (Trace) Ustart= 5.00 Ustop= -5.00 R= 0.10 (V/s)
Freq= 1.0E+006 (Hz) T= 5.0 (deg C)

Step# 8 (Trace) Ustart= 5.00 Ustop= -5.00 R= 0.10 (V/s)
Freq= 1.0E+006 (Hz) T= 10.0 (deg C)

Hit RETURN to continue...

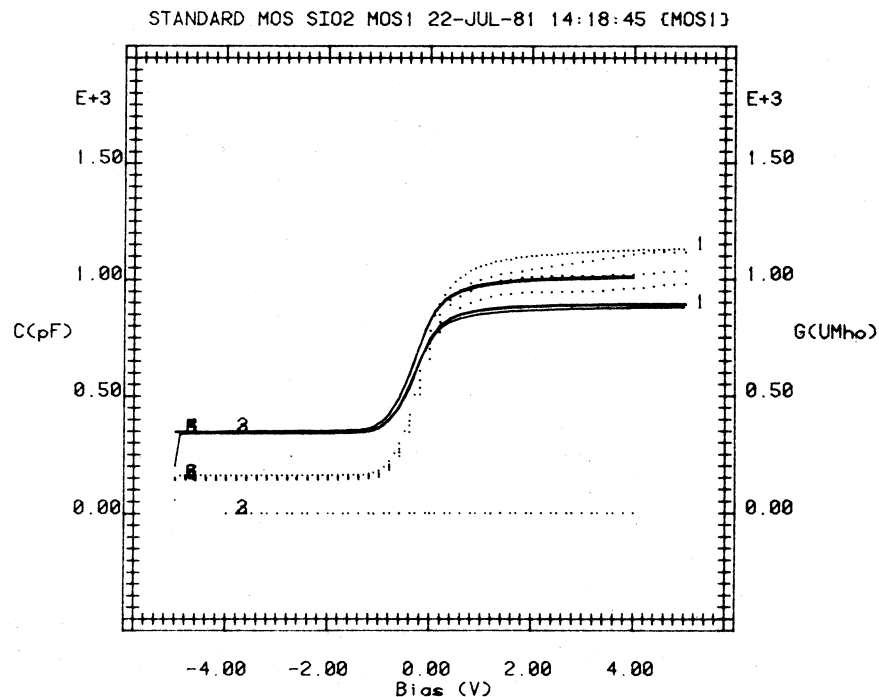


FIGURE 9.

PRINTOUT OF PROCEDURE SAVED, AND PLOT OF DATA SAVED DURING \$CUSTOMCV SESSION IN FIGURE 8.

identifying characters.

Since the plot data is available in digital form, it is possible to write programs which can read the data from the disc and allow the operator to interact with it, often visually, to make the desired parameter measurements. An analog CV system would require tedious manual analysis of raw plots. In this subsection we describe some of the analysis programs we have developed, using further analysis of some of the examples described above as illustrations.

3.2.1 $\%CVPLOT$. This simply allows one to plot data stored in $\%CVLIB$ either to the screen of the computer, or to the plotter. Various automatic and manual scaling options are available. All plots in this report with high resolution "tic" marks on axes are outputs of this program. Note that axis scales are multiplied by 10, 100 etc according to whether E + 1, E + 2, etc. appears on the axis.

3.2.2 $\%CVANAL$. This program uses just the CV profile data, ignoring the G-V data. It finds C_{max} and C_{min} , computes $C_{flat-band}$, substrate type and concentration and dielectric (usually SiO_2) thickness, and finds flat-band and threshold voltages. The algorithm used for this is given in Appendix A.

Example 1 (continued). Standard CV qualification. The report generated by $\%CVANAL$ for the data plotted in Figure 3 is shown in Figure 10. A useful item is the matrix of all possible flatband voltage differences between traces. For example, the entry in row 2, column 1 is to be interpreted as a Na^+ shift because the procedure STDCV (Figure 3) is a standard MOS CV qualification.

Example 4 (continued). Activation energy for charge injection into plasma-enhanced CVD SiO_2 . When the data in Figure 6 are analysed by $\%CVANAL$, we obtain the analysis in Figure 10 in which the off-diagonal elements in the matrix [(1,2), (2,3), etc.] gives the flat band voltage shifts between successive traces generated by the procedure ACTIV25 (Figure 6). These shifts are caused by soaks at successively higher temperatures. Thus an Arrhenius plot of the off-diagonal matrix elements using the soak temperatures in ACTIV25 gives the activation energy of the mechanism causing the shift.

CV QUAL. PE-17-03-81-2 MASK 1 STDCV 18-MAR-81 08:41:52 (PEMASK1)

AREA : 1.448E-002 (cm²) 2244.4 (mil²)

RAW DATA : Cmax = 2.59E+004 (Pf/cm²), = 375.10 (Pf)
 Cmin = 1.48E+004 (Pf/cm²), = 214.10 (Pf)
 Cfb = 2.35E+004 (Pf/cm²), = 340.45 (Pf)

SUBSTRATE : N-type [N= 1.00E+016 (cm⁻³)]
 Max depletion layer width = 3007 (Angs)
 Phi(S) = 3.45 (Volts)

DIELECTRIC: Thickness= 1299 (Angs)
 Diel cons= 3.80

GATE METAL: Aluminum
 Phi(M) = 3.20 (Volts)

FLATBAND AND THRESHOLD VOLTAGES

Trace #	Vfb	Vt
1	-0.01	-2.58
2	-0.67	-3.23
3	-0.10	-2.67

FLATBAND VOLTAGE DIFFERENCE MATRIX

	1	2	3	4	5	6	7	8	9	10
1	0.00	0.66	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-0.66	0.00	-0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	-0.09	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PB2025U WAF 19 ACTIV25 12-MAY-81 16:40:24 (PB2025U/ACT1)

AREA : 7.118E-003 (cm²) 1103.3 (mil²)

RAW DATA : Cmax = 3.46E+004 (Pf/cm²), = 246.00 (Pf)
 Cmin = 4.10E+003 (Pf/cm²), = 29.15 (Pf)
 Cfb = 1.56E+004 (Pf/cm²), = 110.69 (Pf)

SUBSTRATE : P-type [N= 1.24E+014 (cm⁻³)]
 Max depletion layer width = 22298 (Angs)
 Phi(S) = 4.04 (Volts)

DIELECTRIC: Thickness= 974 (Angs)
 Diel cons= 3.80

GATE METAL: Aluminum
 Phi(M) = 3.20 (Volts)

FLATBAND AND THRESHOLD VOLTAGES

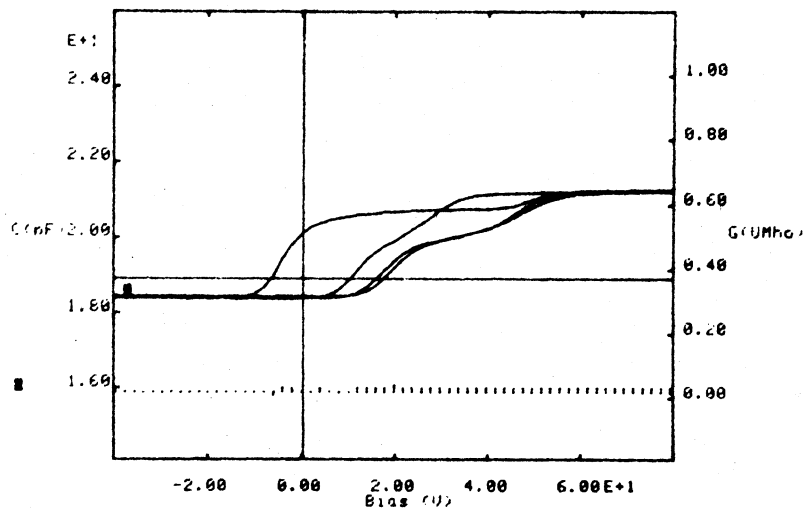
Trace #	Vfb	Vt
1	-6.25	-5.65
2	-6.59	-5.99
3	-7.17	-6.56
4	-8.11	-7.51
5	-9.88	-9.27
6	-14.39	-13.78

FLATBAND VOLTAGE DIFFERENCE MATRIX

	1	2	3	4	5	6	7	8	9	10
1	0.00	0.34	0.91	1.86	3.62	8.14	0.00	0.00	0.00	0.00
2	-0.34	0.00	0.57	1.52	3.28	7.80	0.00	0.00	0.00	0.00
3	-0.91	-0.57	0.00	0.95	2.71	7.22	0.00	0.00	0.00	0.00
4	-1.86	-1.52	-0.95	0.00	1.76	6.28	0.00	0.00	0.00	0.00
5	-3.62	-3.28	-2.71	-1.76	0.00	4.51	0.00	0.00	0.00	0.00
6	-8.14	-7.80	-7.22	-6.28	-4.51	0.00	0.00	0.00	0.00	0.00

FIGURE 10.
OUTPUT OF \$CVANAL FOR EXAMPLES 1 (TOP) AND 4 (BOTTOM)

Position: Intercepts, Repplot (P-I-R)I
 Hit "RETURN" when cursor is positioned
 Long (Y-N)Y
 GAY S. WAFER # 14 DOT(2,0) GAYSHIFT 03-JUL-81 11:36:48 (GAYS14)



CURSOR INTERCEPTS <<

C and G Intercepts for Bias = 0.34

	Cap (pF)	G (uMho)
1	20.25	2.00E-002
2	18.41	2.00E-002
3	18.42	2.00E-002
4	18.45	2.00E-002

Bias Intercepts for C= 18.92 (pF) and G= 3.75E-001 uMho

	C-Bias (V)	G-Bias (V)
1	-7.43	0.00
2	11.56	0.00
3	17.74	0.00
4	16.11	0.00

C-Intercept difference matrix for Bias = 0.34 (V)

	1	2	3	4	5	6	7	8	9	10
1	0.0	1.8	1.8	1.8	0.0	0.0	0.0	0.0	0.0	0.0
2	-1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	-1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	-1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

G-Intercept difference matrix for Bias = 0.34 V

	1	2	3	4	5	6
1	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000
2	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000
3	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000
4	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000

Bias intercept matrix for C = 18.92 (pF)

	1	2	3	4	5	6	7	8	9	10
1	0.00	-18.99	-25.16	-23.54	0.00	0.00	0.00	0.00	0.00	0.00
2	18.99	0.00	-6.18	-4.55	0.00	0.00	0.00	0.00	0.00	0.00
3	25.16	6.18	0.00	1.62	0.00	0.00	0.00	0.00	0.00	0.00
4	23.54	4.55	-1.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Bias intercept matrix for G = 3.75E-001 (uMho)

	1	2	3	4	5	6	7	8	9	10
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

FIGURE 11.

APPLICATION OF \$CVMEAS. DATA WITH CROSSHAIRS DRAWN (TOP) AND
 CORRESPONDING INTERCEPT REPORT.

No. of sections (≤ 0 to replot), Ustart, Uend21, -2, 2

GLEN WAFER # 280 LRG. DOT FREQ200N 19-MAY-81 12:38:41 (GLEN280L)

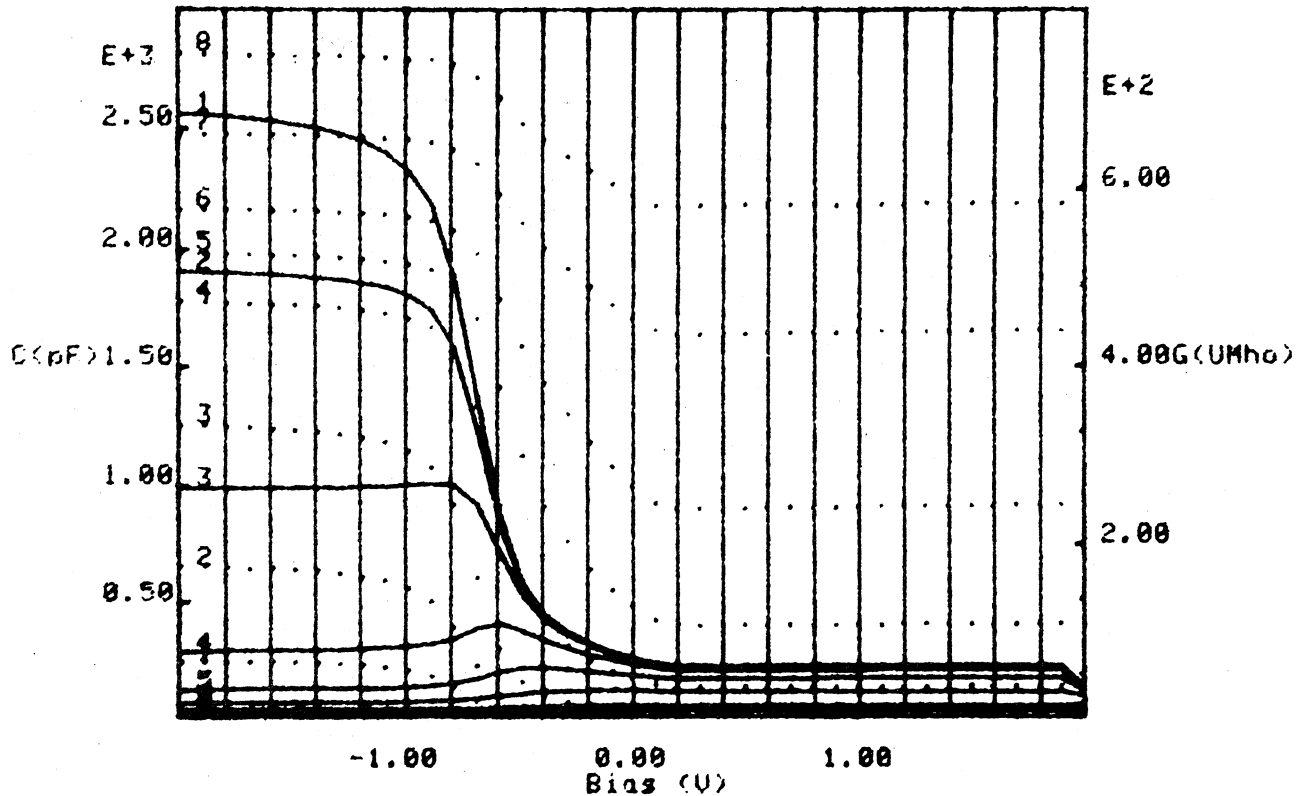


FIGURE 12.

APPLICATION OF \$CVFREQ. CV AND GV DATA AT VARIOUS FREQUENCIES, GENERATED BY THE PROCEDURE IN FIGURE 5, IS SECTIONED AT A SERIES OF BIASES (VERTICAL LINES) PRIOR TO GENERATING FREQUENCY PLOTS.

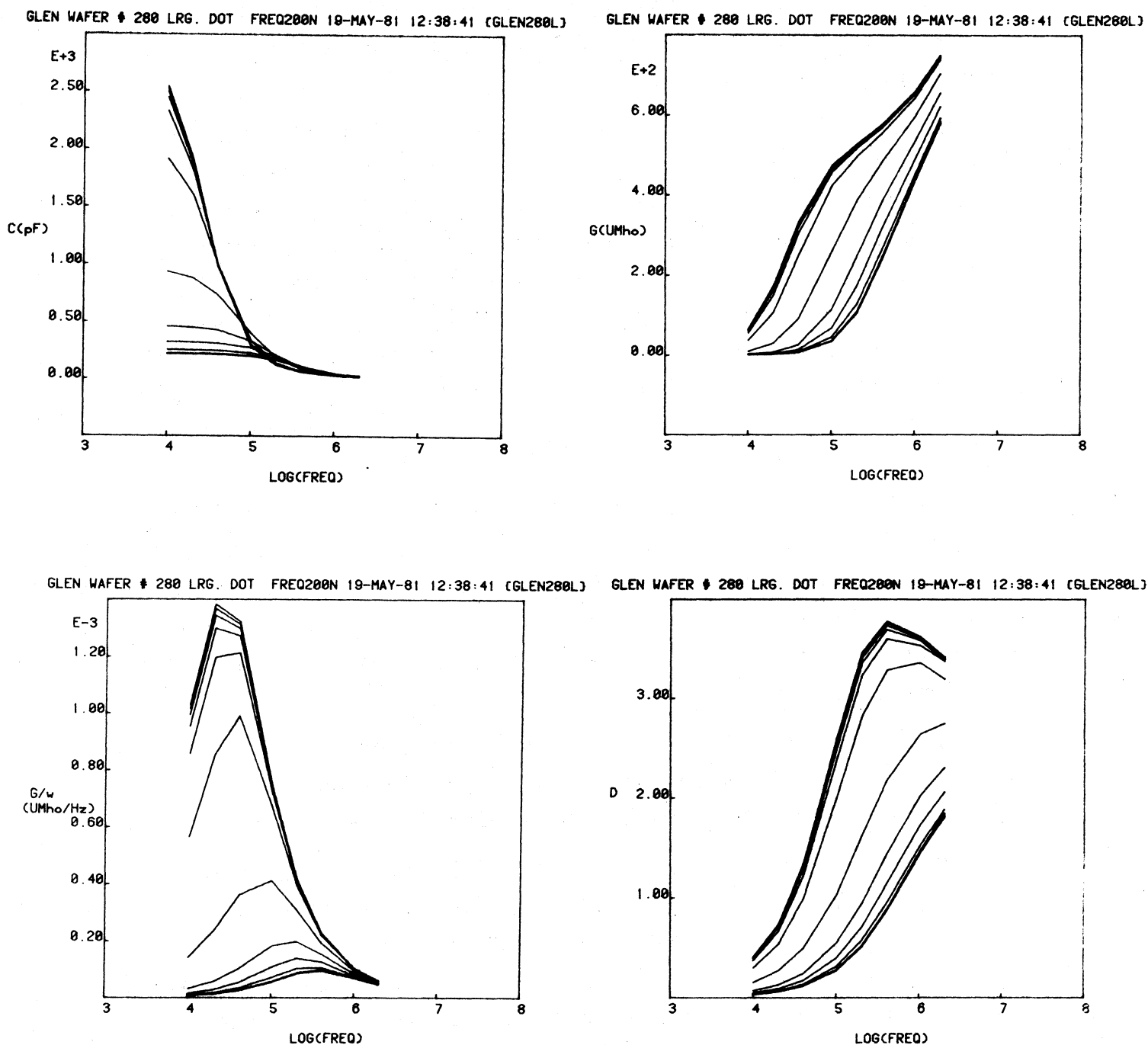


FIGURE 13.
FREQUENCY PLOTS GENERATED FROM THE DATA OF FIGURE 12.

The user will learn to monitor particular entries in the difference table as a function of processing variables according to the procedure definition and his own interests.

3.2.3. `%CVMEAS`. This program gives complete flexibility in measuring intercepts and values of C, G and V at various points on the plots, but carries the analysis no further than this. The program displays the CV plots on the computer's screen and then offers two measurement options. The first allows the user to place the cursor by means of the joystick anywhere on the plot and record the value of C, G, and V at that point and repeat for any number of points. The second option allows one to place the cursor anywhere on the plot and have crosshairs drawn. All intercepts with the crosshairs are found and printed out as well as difference matrices of intercepts.

Example 5 (continued). Polarization kinetics of polyimide. The plot in Figure 7 shows numbered cursor position marks, and below it the corresponding printout of coordinates. The cursor can be placed anywhere on the plot, not necessarily on a curve. In Figure 11 the intercept option has been chosen. The cursor was positioned, crosshairs drawn, and the intercept report generated.

3.2.4. `%CVFREQ`. Often the frequency variation of the four quantities, C, G, G/ω or $D(= G/\omega C)$, where $\omega = 2\pi f$, at various values of bias is useful in determining the dynamical properties of interface states etc.

Example 6. Frequency study of thin thermal SiO_2 on p-type SiO_2 . The procedure in Figure 5 produced the data shown in Figure 12. After plotting the data, the user can "section" the CV and GV traces at a set of bias values. A vertical line is drawn at each of these values, and C, G and f is found for each slice-curve intersection. The user then has the option of plotting any of the four quantities versus $\log(\omega)$; Figure 13. Each curve in the plots in Figure 13 corresponds to a slice, i.e. a value of bias.

3.2.5. `%CVCORRECT`. Sometimes the impedance of the countercontact in an MOS measurement has an appreciable effect on the reading. For example, for thin ($\sim 200 \text{ \AA}$) thermal gate oxides the MOS capacitor impedance can be small enough to be comparable to the backside contact impedance. If C-V

measurements are made on two MOS capacitors of different area, with the same counter contact in each case, then the capacitance and equivalent parallel conductance of the MOS capacitor (per unit area) can be separated from the (total) capacitance and equivalent parallel conductance of the backside contact. This separation assumes negligible fringing effects for the MOS capacitors. The theoretical details of the separation technique are given in Appendix B.

Example 3 (continued). Frequency study of thin thermal (gate) SiO_2 . The two sets of curves generated on a large MOS capacitor, and a small MOS capacitor are used as inputs to %CVCORRECT. See Figure 5. The resulting MOS capacitor impedance and backside contact impedance are then written into the library %CVLIB. The resulting data files can be read and analysed using any of the above CV analysis software. In particular, %CVPLOT was used to generate plots of the separate impedances at the bottom of Figure 5. These results show that most of the frequency dispersion in the original data is due to the back contact.

3.2.6 %CVXFER. This is a utility which permits data to be written to and read from magnetic tape for long-term archival storage.

4. CONCLUSIONS

Developments in computers and instrumentation in the past few years have made it easy to assemble the hardware for a digital computer-controlled CV system to support semiconductor process development. The key to making such a system flexible but convenient, and to exploiting the full potential of the hardware is to develop a carefully thought-out software system. The emphasis of this report has been the description of both the data acquisition software and data analysis software.

The time-consuming effort was the development of the software. Now that this has been done, our system can be duplicated with minimal effort in other laboratories using our software, even if some hardware changes are made. The major constraints are to use a Tektronix 4050-series computer, and a Hewlett-Rackard HP4275A LCR meter.

The software has evolved over a period in response to practical needs, so the system described here is a well-honed tool. Nevertheless, software

changes are continually being made, albeit at a slower rate now, and this will continue. So even in a well-developed system the computer's time will be divided among program development, data analysis, and data acquisition tasks. Considerable improvement in efficiency can be realized if a second computer is mainly dedicated to the first two tasks, while the first computer is dedicated entirely to data acquisition.

The system described in the present report is a subsystem of a larger system other functions of which will be described in subsequent reports.

ACKNOWLEDGEMENTS

The development of the system has been greatly facilitated by the skillful technical support of Dan McGuire. Dan has worked on this project since its inception and has made many valuable suggestions. Oscar Diaz has also helped by fabricating ingenious fixtures and mechanisms. My colleagues, Carl Aspin and Gay Samuelson, were very patient while waiting for the system to become productive. Finally, thanks are due to Melinda Gibbs for typing this report.

APPENDIX A. MOS CV ANALYSIS ALGORITHM IN §CVANAL

Symbol definitions and values:

$$K_s = \text{semiconductor diel const} = 11.7$$

$$K_i = \text{insul diel const.} = 3.82$$

$$N_i = \text{intrinisc carrier conc.} = 1.6 \times 10^{10} \text{ cm}^{-3}$$

$$\frac{RT}{q} = 0.0257 \text{ volts. @ } 298^\circ\text{K}$$

$$\epsilon_0 = 8.85415 \times 10^{-14} \text{ farad/cm}$$

$$q = 1.60206 \times 10^{-19} \text{ coulomb.}$$

1. Trace data, including capacitor area is read from disc, and all capacitances are normalized to area. Hence all capacitances below (C_{\max} etc.) are in units of farad/cm².
2. Computer finds C_{\max} and C_{\min} from plot(s).
3. Decides on type of substrate using following criterion:
 if $V_{\max} > V_{\min}$ then n-type
 otherwise p-type
 where V_{\max} = bias at C_{\max} etc.
4. Calculates maximum depletion width (W_m)

$$\frac{1}{C_{\min}} = \frac{1}{C_D} + \frac{1}{C_{\max}}$$

C_D = depletion capacitance, C_{\max} = oxide capacitance

$$\text{So } C_D = \frac{C_{\min} C_{\max}}{C_{\max} - C_{\min}} = \frac{\epsilon_0 K_s}{W_m}$$

thus

$$W_m = \frac{\epsilon_0 K_s (C_{\max} - C_{\min})}{C_{\max} C_{\min}} \quad (1)$$

5. Calculates substrate doping. W_m is related to substrate doping in following way: (N = subst. doping)

$$W_m = \sqrt{\frac{4\epsilon_0 K_s kT \ln(N/n_i)}{q^2 N}} \quad (2)$$

[see SM. Sze p 436, eq (28)]

With W_m known, solve for N , but the equation is transcendental, so must use iterative solution.

5. Continued -

Rearrange (2) to give

$$N = \frac{4\epsilon_o K_s kT \ln(N/n_i)}{q^2 W_m^2}$$

$$\text{or } N = N_o \ln(N/n_i)$$

(3)

where N_o is a constant given by

$$N_o = \frac{4\epsilon_o K_s}{q W_m^2} \times \frac{kT}{q}$$

To solve (3) for N , define N_j as the j^{th} estimate of N and start with

$$N_1 = 10n_i$$

Then iterate finding the $j + 1^{\text{th}}$ estimate from the j^{th} using

$$N_{j+1} = N_o \ln(N_j/n_i)$$

Continue iterating until $\frac{N_{j+1} - N_j}{N_j} < 0.1\%$

Then $N = N_{j+1}$ [takes 4 or 5 iterations].

6. The oxide thickness is found directly from C_{max} : (t = oxide thickness)

$$\begin{aligned} C_{\text{max}} &= \frac{\epsilon_o K_i}{t} \\ t &= \frac{\epsilon_o K_i}{C_{\text{max}}} \end{aligned} \quad (4)$$

7. With the results of steps 5 and 6 above we are in a position to compute the flat-band capacitance C_{FB} .

From S.M. Sze, p 435, eq(26)

$$C_{\text{FB}} = \frac{\epsilon_o K_i}{t + \frac{K_i}{K_s} \sqrt{\frac{kT \epsilon_o K_s}{N q^2}}} \quad (5)$$

8. The computer now searches for the voltages where the capacitance of each trace crosses C_{FB} .

9. The threshold voltages corresponding to these flat-band voltages are computed as follows:

$$V_T = V_{FB} + 2\phi_f - \frac{Q_B}{C_{\max}}$$

where

$$\phi_f = \pm \frac{kT}{q} \ln \frac{N}{n_i} \quad \begin{array}{l} + \text{ sign for p-type} \\ - \text{ sign for n-type} \end{array}$$

$$Q_B = \mp qNW_m \quad \begin{array}{l} - \text{ sign for p-type} \\ + \text{ sign for n-type} \end{array}$$

i.e.

$$V_T = V_{FB} \mp \left(\frac{qNW_m}{C_{\max}} + \frac{2kT}{q} \ln \frac{N}{n_i} \right) \quad \begin{array}{l} - \text{ for n-type} \\ + \text{ for p-type} \end{array} \quad (6)$$

APPENDIX B CORRECTION FOR COUNTER CONTACT IMPEDANCE EFFECTS

When the magnitude of the counter contact impedance becomes comparable to the impedance of the MOS capacitor on the front of the wafer, then the measured impedance is not characteristic of the MOS capacitor alone. However, one can separate the MOS capacitor and counter contact contributions to the measured impedance by measuring two different area capacitors and then assuming that the MOS capacitor impedance will scale with area, whereas the counter contact impedance will be the same for each capacitor.

The measured impedances for dots with two different areas are (see Figure B1)

$$Z_T^1 = \frac{Z}{A_1} + Z_b$$

$$Z_T^2 = \frac{Z}{A_2} + Z_b$$

Solving for Z and Z_b , we get

$$Z = \frac{A_1 A_2}{A_2 - A_1} (Z_T^1 - Z_T^2) \quad B1$$

$$Z_b = \frac{A_2 Z_T^2 - A_1 Z_T^1}{A_2 - A_1} \quad B2$$

The meter measures the capacitance and the equivalent parallel conductance (C and G) where

$$Z_T^1 = (G_1 + i\omega C_1)^{-1} \quad (\text{area } A_1) \quad B3a$$

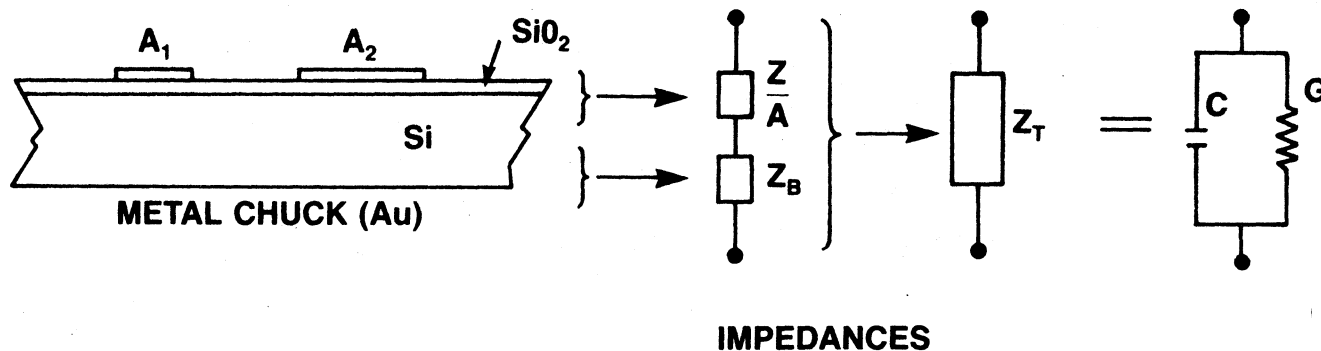
$$Z_T^2 = (G_2 + i\omega C_2)^{-1} \quad (\text{area } A_2) \quad B3b$$

whereas we are interested in C_b, G_b , and c and g where

$$Z_b = (G_b + i\omega C_b)^{-1} \quad B4$$

$$Z = (g + i\omega c)^{-1} \quad B5$$

where C_b and G_b are the parallel counter contact capacitance and conductance and c and g are the same quantities, per unit area, for the MOS capacitor.



Z ≡ IMPEDANCE / UNIT AREA OF MOS CAPACITOR

Z_B ≡ BACKSIDE (COUNTERCONTACT) TOTAL IMPEDANCE

Z_T ≡ TOTAL MEASURED IMPEDANCE

A₁, A₂ ARE CAPACITOR AREAS

FIGURE B1. RELATIONSHIP OF MEASURED CAPACITANCE AND EQUIVALENT PARALLEL CONDUCTANCE TO COMPONENT IMPEDANCES.

Substitution of B3, B4 and B5 into B1 and B2, and separation of real and imaginary parts yields

$$g = \frac{A_2 - A_1}{A_2 A_1} \frac{G_2 G_1 (G_2 - G_1) + \omega^2 (G_1^2 C_2^2 - G_2 C_1^2)}{(G_2 - G_1)^2 + \omega^2 (C_2 - C_1)^2} \quad B6a$$

$$c = \frac{A_2 - A_1}{A_2 A_1} \frac{G_2^2 C_1 - G_1^2 C_2 + \omega^2 C_1 C_2 (C_2 - C_1)}{(G_2 - G_1)^2 + \omega^2 (C_2 - C_1)^2} \quad B6b$$

$$G_b = \frac{(A_2 - A_1)(G_1 G_2 (A_2 G_1 - A_1 G_2) + \omega^2 (A_2 C_1^2 G_2 - A_1 C_2^2 G_1))}{(A_2 G_1 - A_1 G_2)^2 + \omega^2 (A_2 C_1 - A_1 C_2)^2} \quad B6c$$

$$C_b = \frac{(A_2 - A_1)(A_2 G_1^2 C_2 - A_1 G_2^2 C_1 + \omega^2 C_1 C_2 (A_2 C_1 - A_1 C_2))}{(A_2 G_1 - A_1 G_2)^2 + \omega^2 (A_2 C_1 - A_1 C_2)^2} \quad B6d$$

At each value of bias, the computer program, %CVCORRECT, takes A_1 , C_1 and G_1 from one file in %CVLIB and A_2 , C_2 and G_2 from another generated by the identical procedure in %CVPROC, does the calculations in Equations B6, and then writes the results to two other files in %CVLIB. There is a program to generate fake data to test %CVCORRECT.