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PARTICLE MONITORING/FILTRATION TRENDS

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	55	Particulate Filtration of Chemicals, Gases and Photoresist <i>Every fluid that comes into contact with IC surfaces is a potential source of contamination which will affect yields. For this reason filtration of these fluids at the point of use is essential to obtain high yields.</i>
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COVER: Sampling clean room air with an isokinetic probe and a light scattering particle monitor is most rewarding when the readings obtained are un-"event"-ful. Good particle-monitoring programs can produce dramatic results in increased yields. For more details on particle monitoring, see the article that begins on page 35. (Photograph courtesy of Dryden Engineering, Santa Clara, Calif.)

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A Computer-Controlled CV Characterization System

Recent developments in computer-controlled instrumentation make possible greater sophistication in CV measurements in the process development environment, without sacrificing throughput.

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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. This 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, and so forth. 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-1970s when the General-Purpose Interface Bus or GPIB (also known as the IEEE-488 bus or, according to Hewlett-Packard, as the Hewlett-Packard Interface Bus [HPiB]) came into common

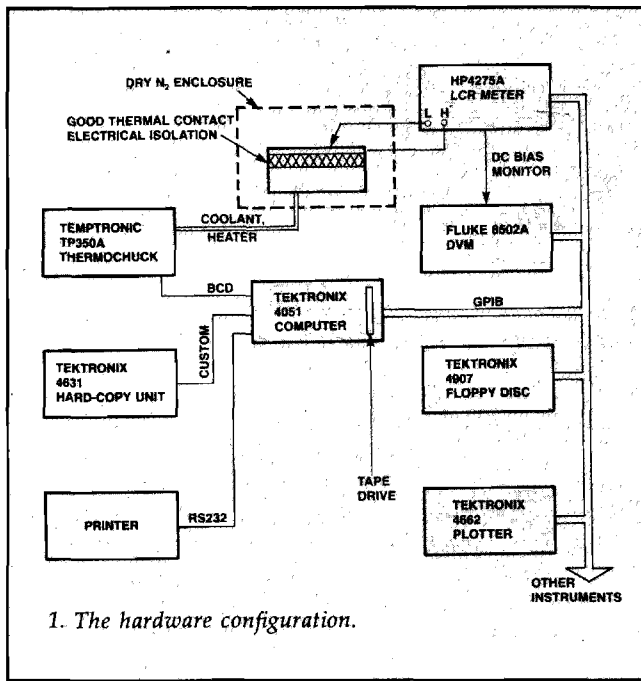
use, and especially since 1979 when Hewlett-Packard introduced the HP4275A LCR Meter, it has become possible to conveniently build a computer-controlled digital system which overcomes the problems of analog systems, and which affords significant additional advantages. The GPIB has made it easy to define 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 Motorola's Process Technology Laboratory (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 will not be given here.

The hardware system

Although interconnection of the elements of the hardware system is easy, choice of the elements themselves involves some nontrivial 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, e.g., BASIC, including communication with peripherals with simple input/output commands. The display peripherals include a 1200 baud matrix printer (a slower printer causes inconvenient delays), 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. It also provides 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 sophisticated software systems with interacting files and libraries of files for both data and programs. 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. 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 10 kHz to 10 MHz in 1-2-4 steps at any bias in the range $-99.9 \text{ V} \leq V_{\text{bias}} \leq 99.9 \text{ V}$. The actual bias seen by 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 (TransEra 632-BCD). All of the equipment is protected from line power fluctuations by an isolation transformer. The hardware configuration is summarized in Fig. 1.

The software system

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

Data acquisition

This function is implemented with three programs, \$CVPROCDEF, \$CUSTOMCV, and \$AUTOCV and a

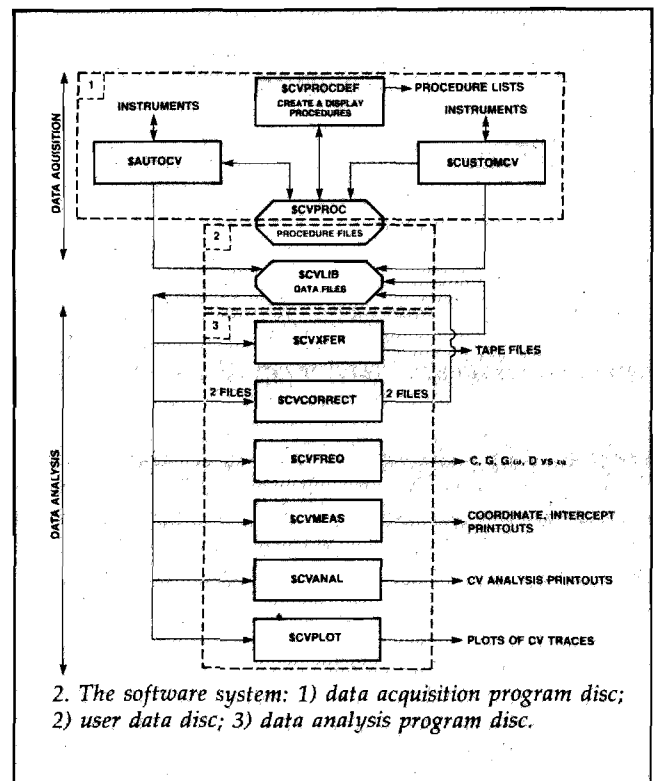
library of data files named \$CVPROC.

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 (V/s) at a frequency of F(Hz) and temperature T ($^\circ\text{C}$). 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



CV PROCEDURE DEFINITION

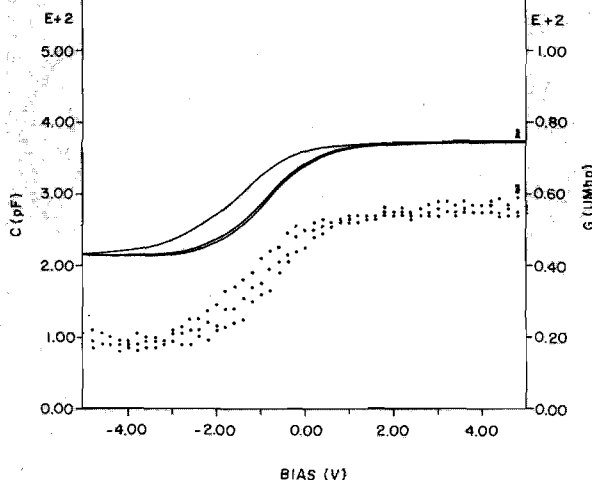
Old Procedure Name: STDCV

- Step #1 (Soak) Time = 1 (sec) Temp = 200.0 (deg C) Bias = 0.00
- Step #2 (Trace) Vstart = 5.00 Vstop = -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) Vstart = 5.00 Vstop = -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) Vstart = 5.00 Vstop = -5.00 R = 0.10 (V/s)
Freq = 1.0E+006 (Hz) T = 25.0 (deg C)

Hit RETURN to continue...

3a. Standard MOS qualification procedure.

CV QUAL. PE-17-03-81-2 MASK1 STDCV 18-MAR-81 08:41:52 (PEMASK1)



3b. Plot generated by thermal SiO₂ using procedure in Fig. 3a. C: solid lines. G: dotted lines.

CV PROCEDURE DEFINITION

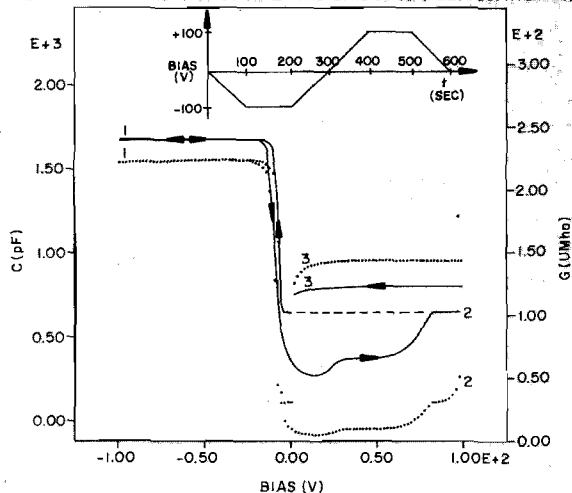
Old Procedure Name: HYST100MID

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

Hit RETURN to continue...

4a. Hysteresis procedure.

PB2025U DOT2 WAF16 HYST100MID 27-FEB-81 18:39:52 (PB2025U/HYSM121)



4b. Hysteresis traces showing charge injection generated from procedure in Fig. 4a. Plasma-enhanced CVD SiO₂.

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, V_{bias}. 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 any value within the range of the measurement equipment:

- 99.9 V ≤ Vstart, Vstop, Vbias ≤ 99.9 V
- F = 10 kHz - 10 MHz in 1-2-4 steps
- 30°C ≤ T ≤ 200°C
- time ≥ 1 s

R (ramp rate) can have any value (V/s)

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 s) 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 %CVPROC-DEF 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 Fig. 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 Fig. 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 %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 Fig. 4a. This subjected the sample to the bias-time profile shown as the inset in Fig. 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)

CV PROCEDURE DEFINITION

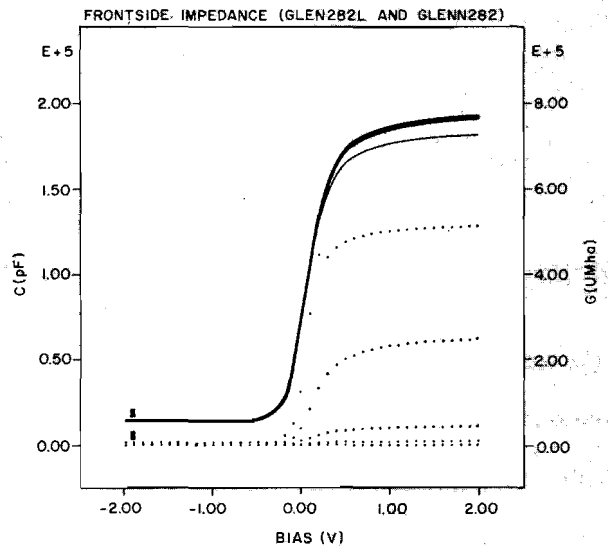
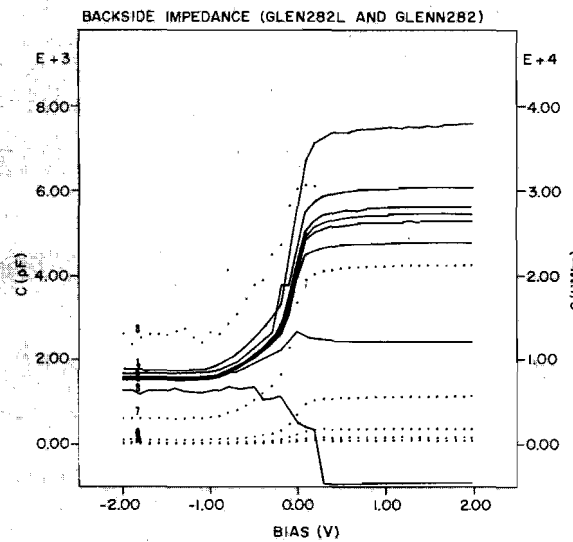
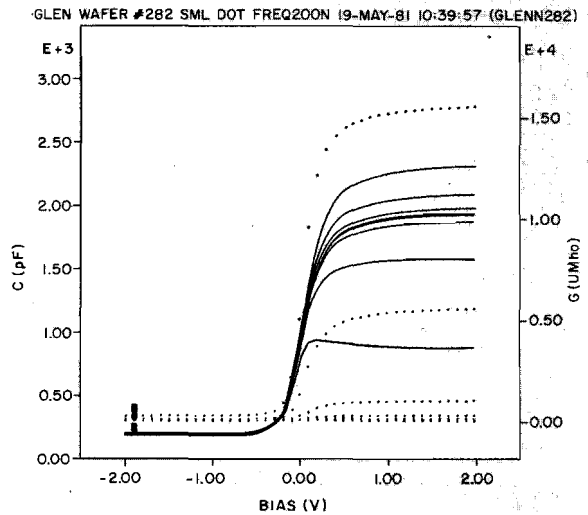
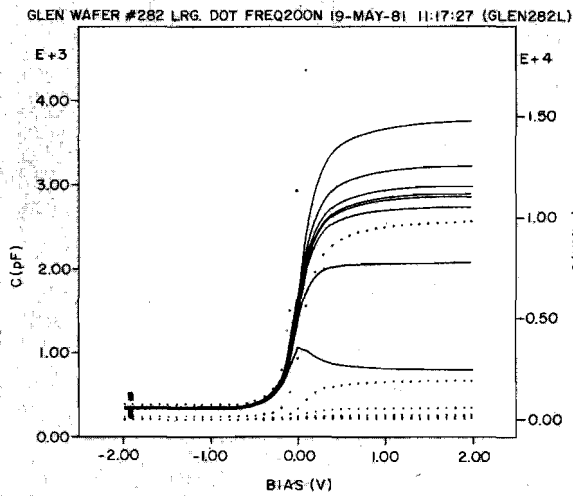
Old Procedure Name: FREQ200N

Step #1	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 1.0E+004 (Hz) T = 25.0 (deg C)
Step #2	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 2.0E+004 (Hz) T = 25.0 (deg C)
Step #3	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 4.0E+004 (Hz) T = 25.0 (deg C)
Step #4	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 1.0E+005 (Hz) T = 25.0 (deg C)
Step #5	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 2.0E+005 (Hz) T = 25.0 (deg C)
Step #6	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 4.0E+005 (Hz) T = 25.0 (deg C)
Step #7	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 1.0E+006 (Hz) T = 25.0 (deg C)
Step #8	(Trace)	Vstart = 2.00 Vstop = -2.00 R = 0.02 (V/s)
		Freq = 2.0E+006 (Hz) T = 25.0 (deg C)

Hit RETURN to continue...

LARGE
AREA CV
DOT

SMALL
AREA CV
DOT



5. Top: Frequency series procedure.
Middle: Traces generated on small and large dots.
Bottom: Output of \$CVCORRECT. Thermal SiO₂.

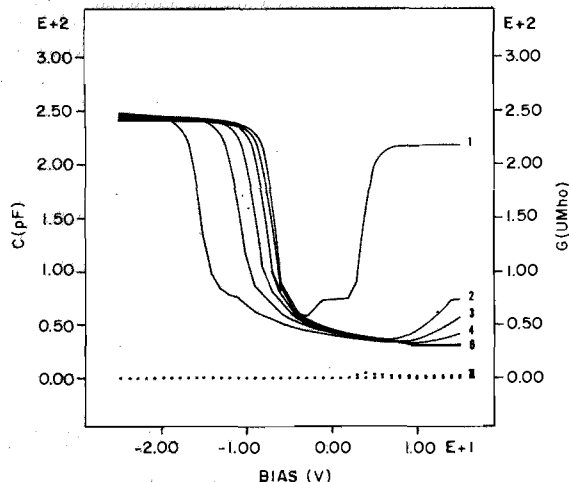
---CV PROCEDURE DEFINITION---

Old Procedure Name: ACTIV25

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

Hit RETURN to continue ...

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



6. Top: Procedure to determine activation energies. Bottom: Traces generated by this procedure. Plasma-enhanced CVD SiO₂.

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 Fig. 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 Fig. 6 has standard room-temperature traces inter-

leaved 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 \$AUTO CV are also shown in Fig. 6. The separation between successive traces increases with temperature. This data will be analysed further below.

Example 5. Polarization kinetics of polyimide. The procedure in Fig. 7 was run on a composite film with 1.4 μm of polyimide on 1000 Å of thermal SiO₂. 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

---CV PROCEDURE DEFINITION---

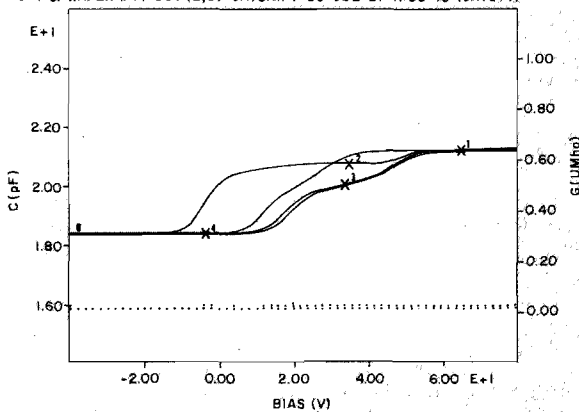
Old Procedure Name: GAYSHIFT

- Step # 1 (Trace) Vstart= 100.00 Vstop= -100.00 R= 1.00 (V/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)
- Step # 2 (Soak) Time= 1 (sec) Temp= 200.00 (deg C) Bias= 0.00
- Step # 3 (Soak) Time= 60 (sec) Temp= 200.00 (deg C) Bias= -5.00
- Step # 4 (Soak) Time= 1 (sec) Temp= 200.00 (deg C) Bias= 0.00
- Step # 5 (Trace) Vstart= 100.00 Vstop= -100.00 R= 1.00 (V/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)
- Step # 6 (Soak) Time= 1 (sec) Temp= 200.00 (deg C) Bias= -0.00
- Step # 7 (Soak) Time= 300 (sec) Temp= 200.00 (deg C) Bias= -5.00
- Step # 8 (Soak) Time= 1 (sec) Temp= 200.00 (deg C) Bias= 0.00
- Step # 9 (Trace) Vstart= 100.00 Vstop= -100.00 R= 1.00 (V/s)
Freq= 1.0E+005 (Hz) T= 25.0 (deg C)
- Step #10 (Soak) Time= 1 (sec) Temp= 200.00 (deg C) Bias= 0.00
- Step #11 (Soak) Time= 900 (sec) Temp= 200.00 (deg C) Bias= -5.00
- Step #12 (Soak) Time= 1 (sec) Temp= 200.00 (deg C) Bias= 0.00
- Step #13 (Trace) Vstart= 100.00 Vstop= -100.00 R= 1.00 (V/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 11:36:48 (GAYS14)



>> CURSOR POSITIONS <<

Position	Bias (V)	Cap (pF)	G (μMho)
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

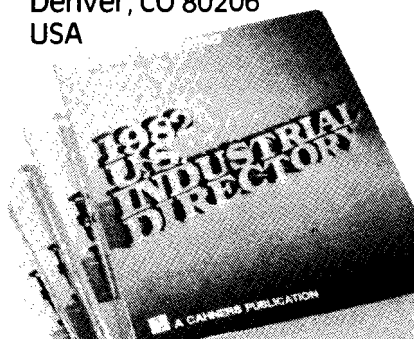
7. Kinetics study of polyimide. Top: Procedure with dummy soaks. Middle: Curves generated by procedure showing cursor positions. Bottom: Cursor coordinates.

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CUSTOM CV PLOTTING

Is chuck Hi or Lo (H/L)H

Enter plot caption and hit "RETURN" to continue
STANDARD MOS SI02

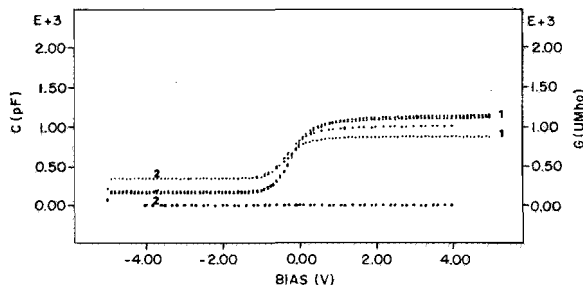
Dot area (cm²)01503

Save procedure (Y/N)Y

New procedure filenameMOS1

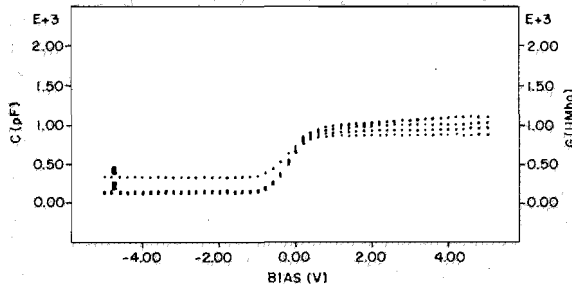
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)N
Vstart,Vstop,R,F,T
-5,5,.05,1E6,25
Plot Scale (Prev/New)N
Vmin,Vmax,Cmin,Cmax,Gmin,Gmax
-5,5,0,2000,0,2000
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)S
Time/Temp/Bias
30,50,2
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)N

Vstart,Vstop,R,F,T
4,-4,.08,1E4,25
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)N
Vstart,Vstop,R,F,T
5,-5,.1,1E6,0
Plot Scale (Prev/New)P
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)N
Vstart,Vstop,R,F,T
5,-5,.1,1E6,5
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)T
Trace Params (Prev/New)N

Vstart,Vstop,R,F,T
5,-5,.1,1E6,10
Hit "RETURN" to start run...
Trace/Soak/Clear/Quit (T/S/C/Q)Q
Save data (Y/N)Y
FilenameMOS1



8. Screen images for \$CUSTOMCV real-time data acquisition session.

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 Fig. 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 Fig. 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; 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 Fig. 9.

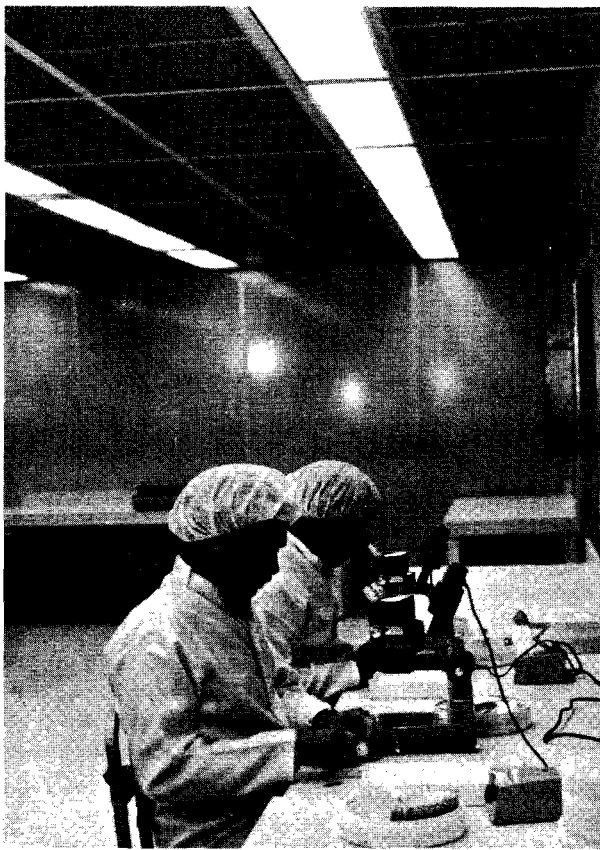
Data analysis

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 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 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.

%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.

%CVANAL. This program uses just the CV profile



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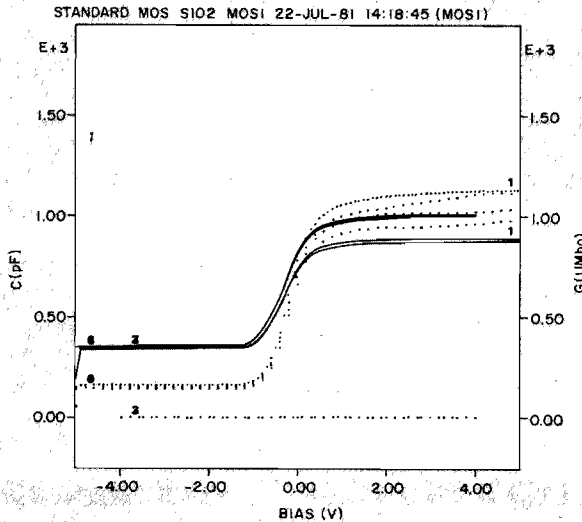
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CV PROCEDURE DEFINITION

Old Procedure Name: MOS1
 Step # 1 (Trace) Vstart= -5.00 Vstop= 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) Vstart= 4.00 Vstop= -4.00 R= 0.06 (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) Vstart= 4.00 Vstop= -4.00 R= 0.06 (V/s)
 Freq= 1.0E+004 (Hz) T= 25.0 (deg C)
 Step # 6 (Trace) Vstart= 5.00 Vstop= -5.00 R= 0.10 (V/s)
 Freq= 1.0E+006 (Hz) T= 0.0 (deg C)
 Step # 7 (Trace) Vstart= 5.00 Vstop= -5.00 R= 0.10 (V/s)
 Freq= 1.0E+006 (Hz) T= 5.0 (deg C)
 Step # 8 (Trace) Vstart= 5.00 Vstop= -5.00 R= 0.10 (V/s)
 Freq= 1.0E+006 (Hz) T= 10.0 (deg C)
 Hit RETURN to continue ...



9. Printout of procedure saved, and plot of data saved during \$CUSTOMCV session in Fig. 8.

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 flatband 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 Fig. 3 is shown in Fig. 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 (Fig. 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 Fig. 6 are analysed by \$CVANAL, we obtain the analysis in Fig. 10, in which the off-diagonal elements in the matrix [(1,2), (2,3), etc.] give the flat band voltage shifts between successive traces generated by the procedure ACTIV25 (Fig. 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.

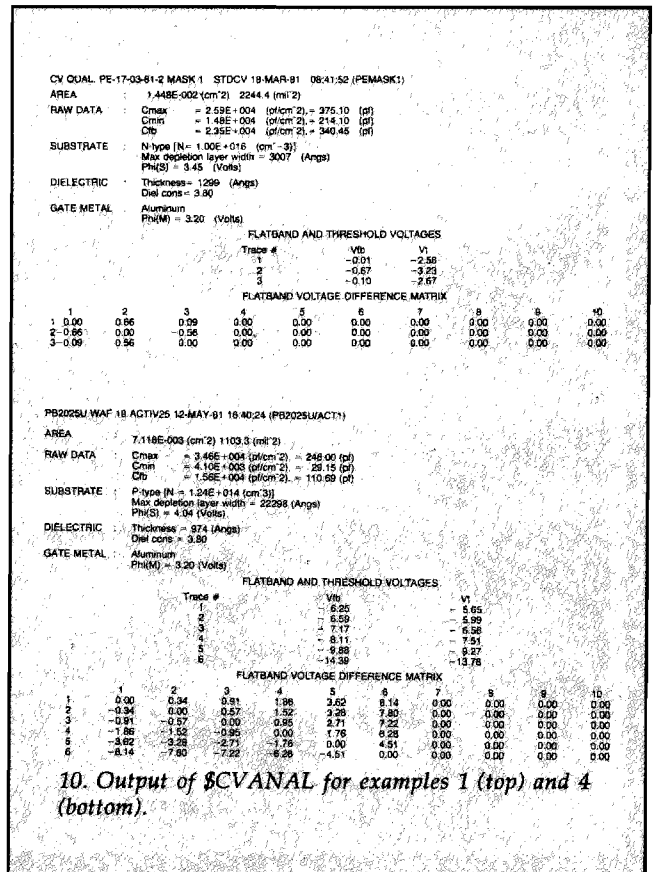
The user will learn to monitor particular entries in the difference table as a function or processing variables according to the procedure definition and his own interests.

\$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 the 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, as well as difference matrices of intercepts, are found and printed out.

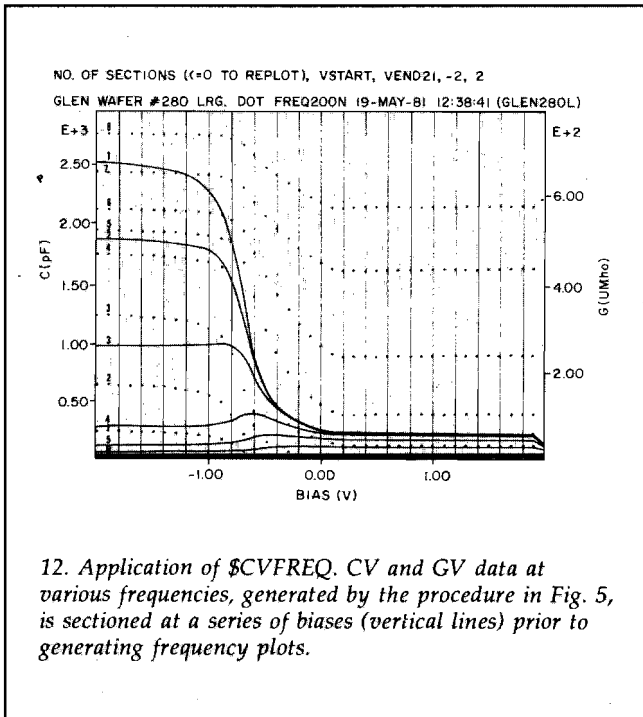
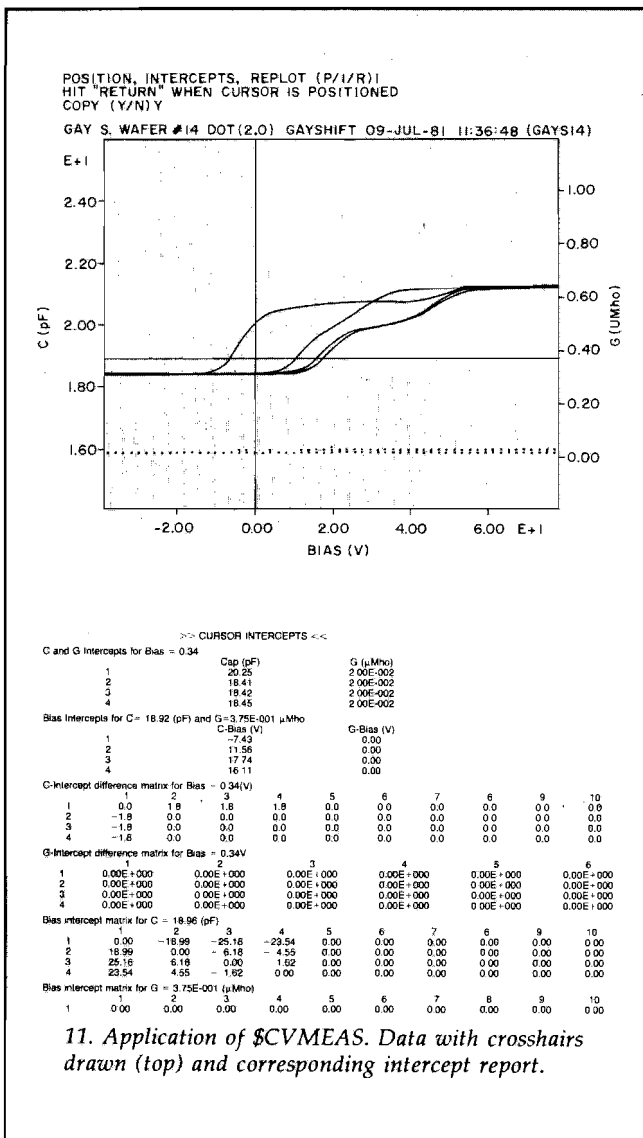
Example 5 (continued). Polarization kinetics of polyimide. The plot in Fig. 7 shows numbered cursor position marks, and below it the corresponding printout of coordinates. The cursor can be placed anywhere on the plot, not necessarily on a curve. In Fig. 11 the intercept option has been chosen. The cursor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

\$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 the interface states, etc.

Example 6. Frequency study of thin thermal SiO_2 on



10. Output of \$CVANAL for examples 1 (top) and 4 (bottom).



P-type SiO₂. The procedure in Fig. 5 produced the data shown in Fig. 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 are found for each slice-curve intersection. The user then has the option of plotting any of the four quantities vs. log (ω); Fig. 13. Each curve in the plots in Fig. 13 corresponds to a slice, i.e., a value of bias.

%CVCORRECT. Sometimes the impedance of the countercontact in an MOS measurement has an appreciable effect on the reading. For example, for thin (≈ 200 A) 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) SiO₂. The two sets of curves generated on a large MOS capacitor, and a small MOS capacitor are used as inputs to %CVCORRECT. See Fig. 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 Fig. 5. These results show that most of the frequency dispersion in the original data is due to the back contact.

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

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 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 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. 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.