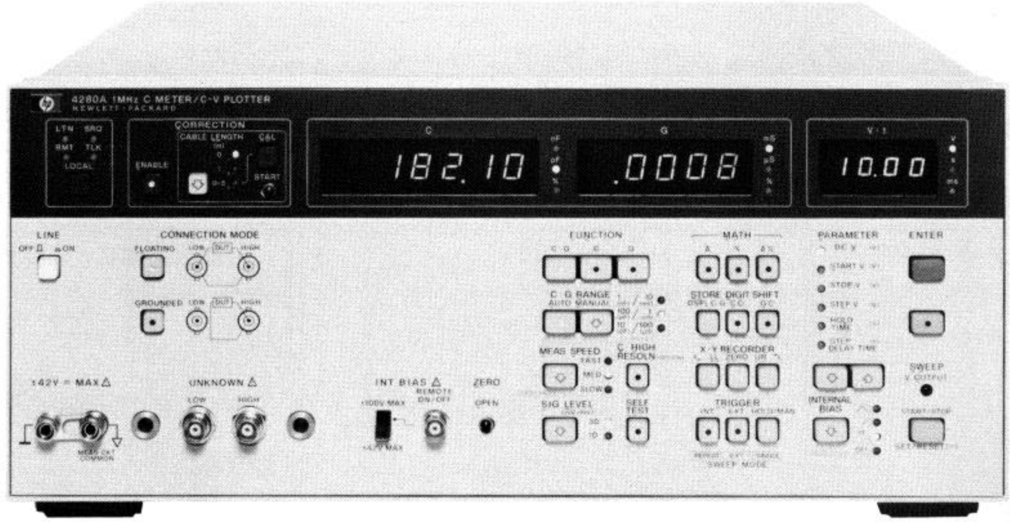
Application Note 322

Analysis of Semiconductor Capacitance Characteristics

Using the HP 4280A 1MHz C Meter/C-V Plotter

HEWLETT PACKARD

CONTENTS



4280A 1MHz C METER/C-V PLOTTER

1. INTRODUCTION

1.1 4280A Applications

The HP model 4280A 1MHz C Meter/C-V Plotter is designed to measure the high-frequency Capacitance-Voltage (C-V) and Capacitance-time (C-t) characteristics of semiconductor devices and materials. When testing Metal-Oxide Semiconductors (MOS) or bipolar transistors, the 4280A provides fully automatic measurements with improved speed and accuracy. The 4280A is ideally suited for wafer process evaluation and for development of new semiconductor devices.

This Application Note explains how to perform reliable C-V and C-t characteristics measurements on semiconductor wafers using the 4280A. This note also contains a procedure for calculating other semiconductor parameters from measured C-V or C-t characteristics.

1.2 4280A Features

■ High Accuracy and High Resolution

The 4280A measures Capacitance (C) and Conductance (G) with 0.1% accuracy and maximum 4-1/2-digit display resolution (5-1/2-digit resolution with opt. 001). The test frequency is fixed at 1 MHz.

The 4280A's CABLE LENGTH CAL capability provides compensation for residuals of the external cables. ZERO OPEN provides compensation for parallel capacitance and conductance in the test fixture. The 4280A's two-terminal pair measurement method virtually eliminates the effects of external noise. All of these 4280A features combine to provide capability for precision C and G measurements.

■ C-V and G-V Measurement Versatility Covers Most Semiconductor Applications

The internal DC bias source can be set to from –100V to +100V with 1mV (3-digit) resolution and 0.1% accuracy. Even minute changes in the C-V or G-V characteristics of a device can be measured accurately.

Automatic swept bias measurements are made by setting START V, STOP V, and STEP V. To allow the device under test to reach stability, HOLD TIME and STEP DELAY TIME can also be set. This means that device characteristics are obtained after the device has attained thermal equilibrium. The 4280A's measurement accuracy insures accurate calculation of device parameters such as flat band voltage (Vfb) and minority carrier lifetime.

■ Easy-to-Obtain C-t Characteristics

When performing C-t measurements, the 4280A's measurement time interval (td) can be set from 10μs (with an external bias source) to 32s, with 10μs resolution and 0.02% accuracy. The response time for a capacitance measurement is only 1μs, so the C-t characteristics of semiconductors having slow or fast transient properties, can be obtained easily. C-t measurements can be used in Zerbst analysis to calculate the minority carrier lifetime and surface generation velocity. Measured C-t values are also used to calculate deep-level traps.

■ Automatic System Applications

Measurements, analysis, and plotting can be performed automatically using the HP-IB. The 4280A outputs measured values in either of two formats: ASCII, or for fast dats output, binary code.

Data measured at each bias point during a sweep are stored in the 4280A's measurement data buffer. All stored data are then transfered to the controller at one time (block-data output) when the sweep ends. Block-data output reduces measurement time significantly.

The 4280A's SYNC OUTPUT and EXT TRIGGER are used to synchronize the 4280A with peripheral equipment, such as bias sources or thermal controllers. A recorder output is also provided for hard copy analog plotters. These features make the HP 4280A an ideal element for automatic C-t or B-T (Bias Temperature) systems.

Table 1-1. 4280A Key Specifications

Measurement Function	C-G : C, G, C · G C-t : C-t, G-t, C · G-t
Test Signal	Frequency : 1 MHz ± 0.01 % OSC Level : 10mVrms, 30mVrms ±10%
Internal DC Bias Source	Function : , , , , Output Range : 0 ~ ±100V, 3 digits Resolution : 1mV (max) Basic Accuracy : 0.1 %
Time Sweep Range	*1 10μs ~ 32s *2 (X number of measurement points)
Measurement Range	C : 1 fF ~ 1.9 nF G : 10 nS ~ 12 mS
Basic Accuracy and Display Digits	0.1 % 4-1/2 digits max. (with opt. 001 C : 5-1/2 digits)

*1 : Using an external bias source
*2 : Max number of measurement points is 9999.

1.3 C-V Characteristics of MOS Structures and pn Junctions

Doping profile, flat band voltage (Vfb), and threshold voltage (Vth) are essential parameters used for process monitoring and for new semiconductor device evaluation. These parameters can be derived from C-V measurements. Benefits can include improved device quality and increased production yield.

■ C-V Characteristics of MOS Structures

Total capacitance of the MOS structure shown in Figure 1-1 consists of oxide-layer capacitance (Cox) and depletion-layer capacitance (Cd). Total capacitance is obtained from the equation below:

$$C = \frac{Cox \cdot Cd}{Cox + Cd}$$

Figure 1-2 shows swept bias C-V characteristics of an n-type MOS structure. Curves (a), (b), and (c) show the characteristics of the structure at low frequency, high frequency, and high frequency with pulsed bias.

The carrier distribution in the MOS structure during accumulation, depletion, and inversion is shown in Figure 1-3.

(1) Accumulation

When positive voltage is applied to the gate, majority carriers (electrons) accumulate on the Si-SiO_2 surface. In this state, Cd is negligible and MOS capacitance is equal to Cox, as shown in Figures 1-2 and 1-3.

(2) Depletion

When the applied voltage goes negative, the majority carriers are repelled from the SiO_2 surface. Donor ions remain as fixed charges, forming the depletion layer. In this state, MOS capacitance consists of Cox and Cd, which varies with the applied gate voltage. The MOS capacitance is calculated from this equation:

$$C = \frac{Cox \cdot Cd}{Cox + Cd}$$

(3) Inversion

As the applied gate voltage becomes more negative, the density of the minority carriers (holes) becomes greater than the density of electrons at the surface of the depletion layer, forming the inversion layer.

When a state of deep inversion is reached, the width of the depletion layer becomes constant. Holes in the inversion layer are supplied by the generation of electron-hole pairs caused by normal thermal agitation. This electron-hole generation is relatively slow. At high frequencies, however, holes cannot be generated fast enough, so MOS capacitance decreases and becomes constant as shown in Figure 1-2 (b). But at lower frequencies, holes can be generated fast enough to replenish the inversion layer. Thus MOS capacitance becomes equal to Cox, as shown in Figure 1-2 for curve (a).

When high-frequency pulsed bias is applied, minority carriers are generated even more slowly than when high frequency is applied. This causes MOS capacitance to decrease even further, as shown in Figure 1-2 (c).

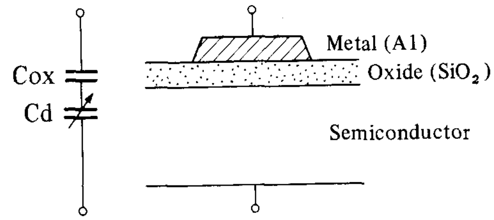


Figure 1-1 MOS Structure

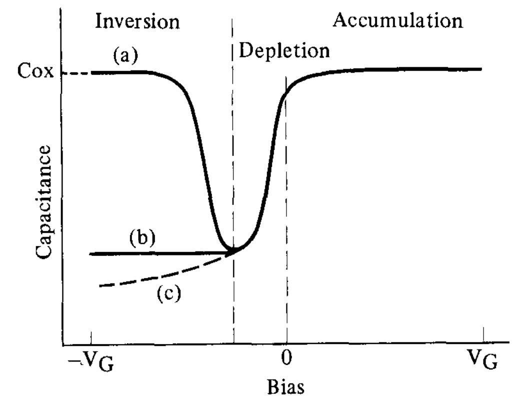


Figure 1-2 C-V Characteristics of a MOS Structure

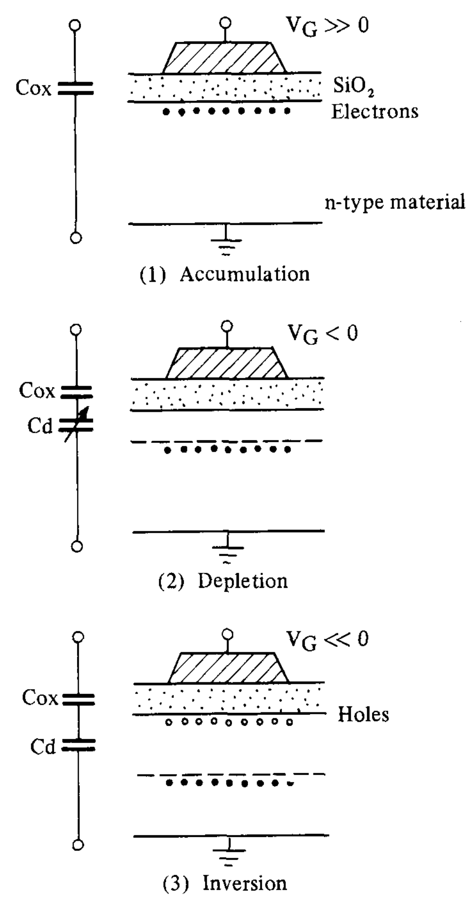


Figure 1-3 Carrier Distribution of a MOS Structure

■ **C-V Characteristics of pn Junctions**

Figure 1-4 shows how the depletion layer of a pn junction is formed by fixed charges (donor and acceptor ions) which concentrate at the junction of the p and n materials. The depletion layer capacitance, Cd, depends on the applied bias voltage. Because Cd depends largely on the impurity concentration of the substrate, the impurity concentration and the built-in potential can be calculated by measuring the pn structure's C-V characteristics. Figure 1-5 shows an example of the C-V characteristics of a pn junction.

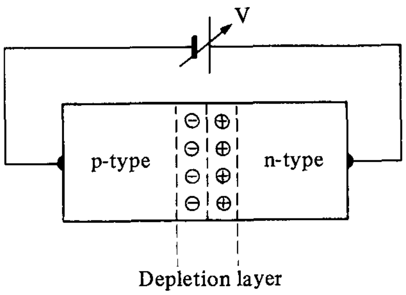


Figure 1-4 pn Junction

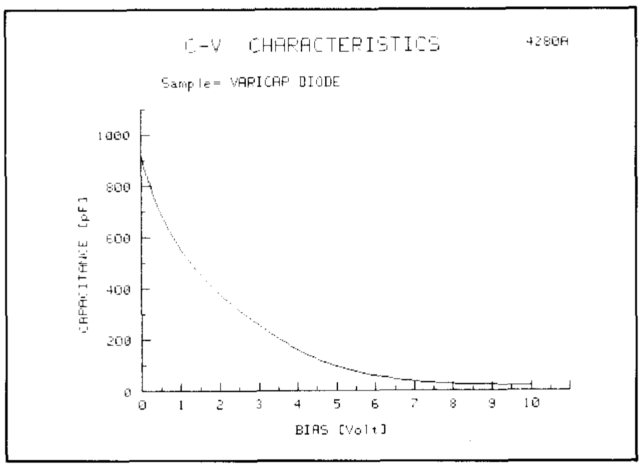


Figure 1-5 C-V Characteristics of a pn Junction

1. 4 Wafer Capacitance Measurements

It has always been difficult to measure wafer capacitance accurately when using a wafer prober, because of such inherent measurement errors as these:

- Stray capacitance and conductance of test fixture and probes
- Mutual inductance and admittance of test cables
- Effects of environmental noise
- Transient line noise when performing grounded device measurements

The HP 4280A, however, virtually eliminates these errors. The 4280A's error correction function, two-terminal pair measurement method, and grounded device measurement capability enable the user to make accurate measurements when using a wafer prober.

When calculating such parameters as the impurity concentration or oxide layer thickness, precise capacitance measurement results are necessary. These results can be fed back to control the wafer production process, thereby increasing production yields, improving device quality, and reducing test cost.

(1) Error Correction

The 4280A has a CABLE LENGTH CALIBRATION function that corrects errors occurring in cables up to five meters long. With the test cable connected to the HIGH terminal (open termination) the 4280A measures the open admittance of the test cable and stores the measured value in internal ROM. The stored value is then used to correct the measured value of the device under test. The corrected value is displayed. CABLE LENGTH CAL doesn't need to be performed when the test cable is zero or one meter.

Next, perform the ZERO OPEN measurement with the test fixture and cables open (see Figure 1-6). In this case the 4280A measures stray capacitance/conductance of the test fixture and stores the measurement in memory.

Last, press the CORRECTION ENABLE key. This causes the 4280A to calculate error corrections, such as the one shown below, then display the true value for the DUT.

$$Y_T = \frac{Y_M\{1 + (R_D + R_S)\, Y_A\}}{1 - Z_O^2 Y_A^2 - Y_M (2Z_O^2 Y_A + R_D + R_S)} - Y_Z$$

(For floating DUT measurements)

Where

Y_M is the measured value (admittance);
Y_T is the true value of the DUT (admittance);
Y_A is the open admittance of the test cable;
Y_Z is the stray admittance of the test fixture;
Z_O is the characteristic impedance of the test cable, a constant (be sure to use the specified cable (HP No. 8120-4195), otherwise accurate error correction will be impossible because of incorrect Z_O); and
R_S and R_D are the residual resistances of the test signal source (R_S) and the measurement circuit or I-V convertor (R_D) (also constants).

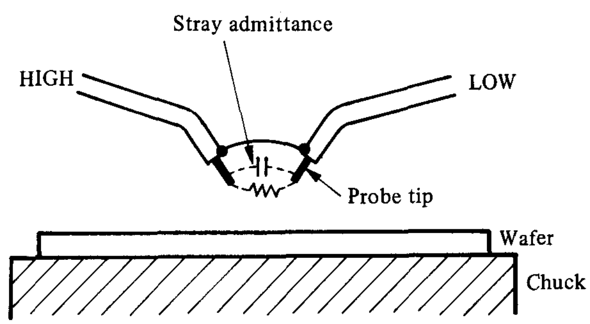


Figure 1-6 Open Condition

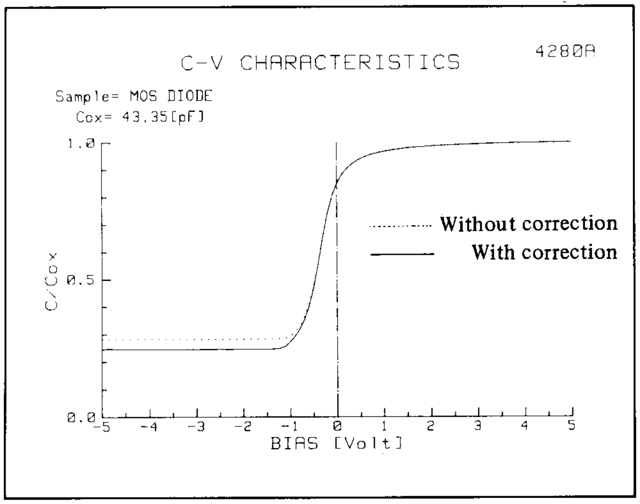


Figure 1-7 Difference in Measurement Results with and without Error Correction

Figure 1-7 shows the difference in the results obtained with and without error correction. It can be seen that the effect of error correction is substantial.

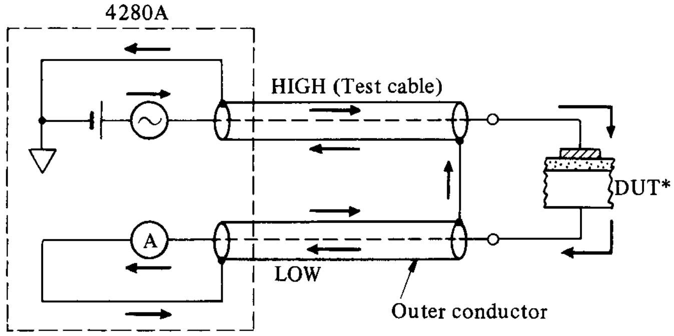
(2) Two-Terminal Pair Measurement Method

Figure 1-8 illustrates the two-terminal pair measurement method. When using a coaxial cable in this method, currents of equal and opposite direction flow down the center conductor and outer conductor. Consequently the effects of mutual interference between High and Low conductors cancel. And the outer conductor acts as a shield to eliminate external noise.

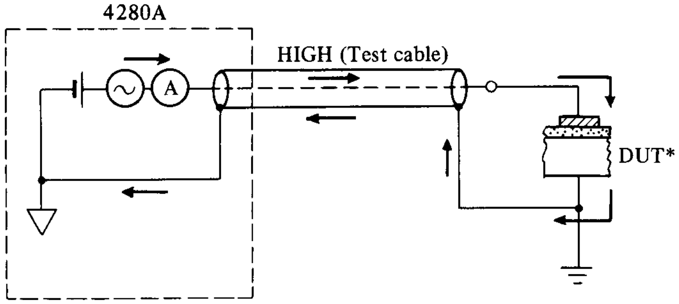
(3) Grounded DUT Measurement

When the device under test is grounded (for example, the chuck of a wafer prober), select the "GROUNDED" CONNECTION MODE. In the grounded mode, the current flowing in the DUT is measured correctly and noise from ground is eliminated. This improves measurement accuracy. The grounded measurement is performed as shown in Figure 1-8 (b).

When testing wafers, connect the 4280A to the prober as shown in Figure 1-9 (a). First cover the prober with a shield box with dark interior to reduce the effects of external noise and light. Next, as shown in Figure 1-9 (b), insulate the test cable from the shield box at the connector to avoid mixing noise from the shield box and the outer conductor of the text cables. Further, as shown in Figure 1-9 (c), use coaxial lead as close to the probe tip as possible to decrease stray admittance; and short the outer conductors of the High and Low cables to prevent errors that could occur if the two-terminal pair were not formed. Use of this technique will help insure stable, accurace measurements.



(a) FLOATING MODE



(b) GROUNDED MODE

*DUT: Device Under Test

Figure 1-8 Two-Terminal Pair Measurement Method

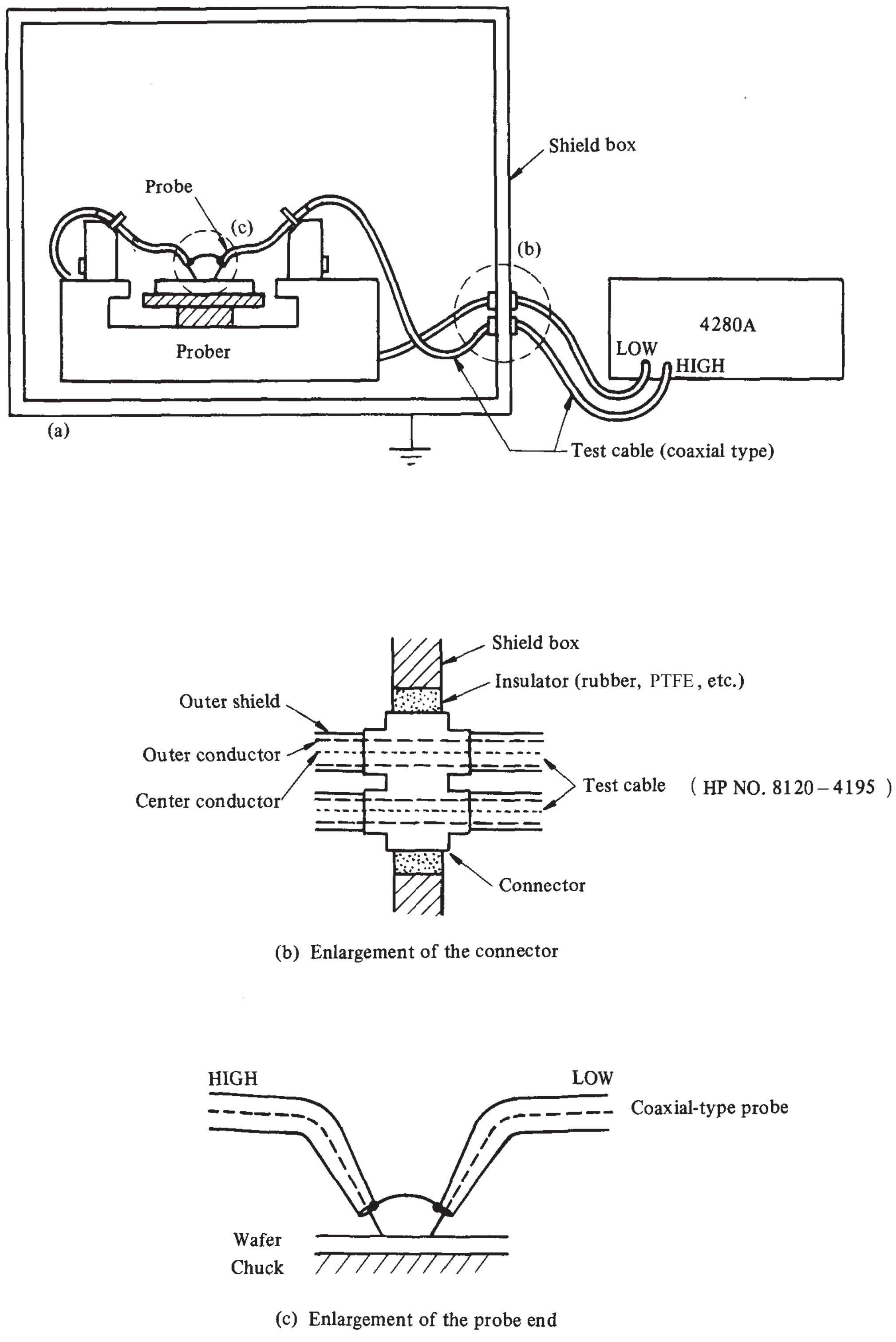


Figure 1-9 How to Connect with the Prober

2. EVALUATION OF C-V/G-V CHARACTERISTICS

This chapter explains how to use the C-V characteristics to calculate other parameters. This analysis is performed when evaluating the quality of semiconductor processes.

2.1 C-V Measurement

Figure 2-1 shows two examples of C-V/G-V measurement using the HP 4280A.

In Figure 2-1 (a), the 4280A is shown controlled by an HP 9826A Desktop Computer. Using an HP-IB controlled prober, many DUTs on a wafer can be tested automatically.

Figure 2-1 (b) shows a system that enables C-V/G-V characteristics to be plotted on an X-Y recorder using RECORDER OUTPUT of the 4280A. Normalized data can be plotted by measuring the capacitance of the oxide layer (Cox) before the sweep. Cox is then used as the normalization constant and the 4280A's math function is used to plot C/Cox.

The next example shows how to make a C-V measurement using the HP-IB system shown in Figure 2-1 (a). (Refer to page 17 for a sample program.)

(Example of Measurment)
Figure 2-2 (a) shows n-type MOS diode C-V characteristics measured under the following conditions:

START V =	-5V
STOP V =	5V
STEP V =	0.05V
HOLD TIME =	10 s
STEP DELAY TIME =	10ms

The C-V characteristics are not accurate for bias from –5 to –2.5V. This is because the measurement was not performed under equilibrium conditions (i.e. the HOLD TIME of 10s was not long enough). Figure 2-2 (b) shows the result of a 40s HOLD TIME, performed at equilibrium. This example shows how the HOLD TIME and STEP DELAY TIME can be chosen to obtain stable measurements. This test was performed using the connection shown in Figure 2-3. (Please see page 15 for details.)

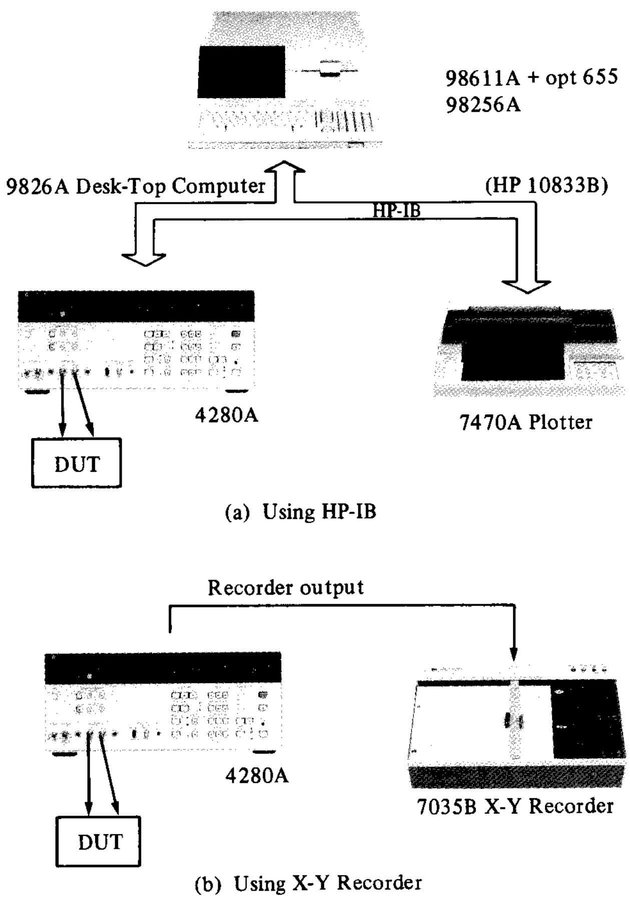
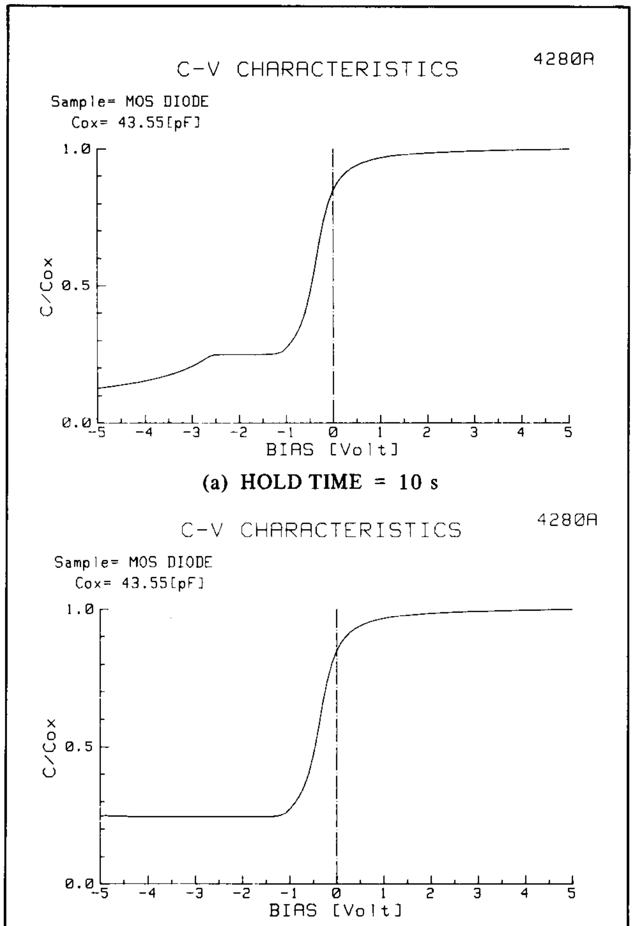


Figure 2-1 The System for C-V Measurement



(a) HOLD TIME = 10 s

(b) HOLD TIME = 40 s

Figure 2-2 C-V Characteristics of MOS Diode

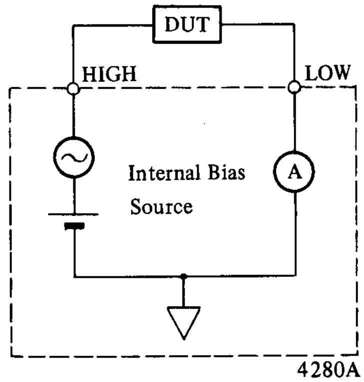


Figure 2-3 Connection (CN10)

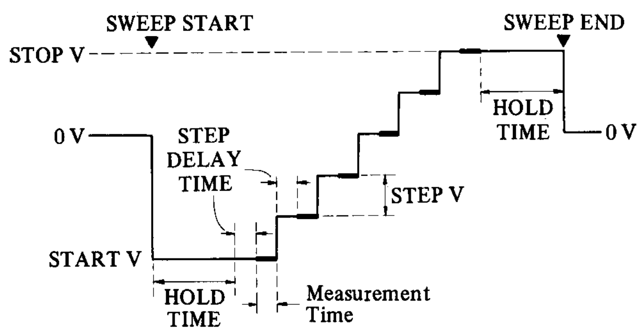
2. 2 How to Calculate Semiconductor Parameters

To calculate semiconductor parameters from C-V characteristics, the Cox (oxide layer capacitance) must be measured and the Nsub (impurity concentration of substrate) obtained from the depletion layer capacitance must be computed. The reliability of parameters largely depends on the accuracy and resolution of measured Cox and depletion layer capacitance. The 4280A can be used to obtain sufficiently accurate parameters for this purpose.

Internal Bias Source Features

The 4280A can provide a step-function ( ) bias sweep internally. The range of the bias sweep and the bias step can be set using START V, STOP V, and STEP V. Also, the HOLD TIME and STEP DELAY TIME are used to insure that the DUT is tested under equiribrium conditions.

Therefore the most suitable measurement conditions for the DUT are obtained.
Four bias sweep modes are available- , , , and , using these modes, the hysteresis of C-V characteristics can be obtained.



START V, STOP V:	0 to ±100 V
STEP V:	0 to 200 V
HOLD TIME:	3 ms to 650 s.
STEP DELAY TIME:	3 ms to 650 s.

(1) **Nsub: impurity concentration of the substrate**
Nsub can be calculated accurately from 4280A capacitance measurement data using the following equations, which assume that Nsub is constant in bulk.

$$Nsub = \frac{4 \cdot |\phi f|}{q \cdot \epsilon_0 \cdot \epsilon_{si}} \cdot \left(\frac{Csmin}{A}\right)^2$$

$$\phi f = \pm \frac{k \cdot T}{q} \ln\left(\frac{Nsub}{ni}\right) \begin{pmatrix} + : \text{p-type} \\ - : \text{n-type} \end{pmatrix}$$

where

ϕf is the Fermi potential, in Volts;
Csmin is the minimum depletion layer capacitance, in Farads;
A is the area of the gate (A1), in cm^2;
ni is the intrinsic carrier concentration per cm^3;
ϵ_0 is the free space permittivity (8.854×10^{-14} F/cm);
ϵ_{si} is the dielectric constant of Si (11.7);
q is the magnitude of electronic charge (1.602×10^{-19} Coulomb);
k is the Boltzmann constant (1.38×10^{-23} J/K); and
T is the absolute temperature, in K.

Figure 2-2(b) shows that $Csmin = 13.81 \times 10^{-12}$ F. And by the method of successive approximation, we find Nsub:

$$Nsub = 1.406 \times 10^{15} \ [1/cm^3]$$

where

$$A = 0.001 \ cm^2, \text{ and}$$
$$T = 293 \text{ K.}$$

(2) **Vfb: flat band voltage**
For practical MOS structures, a negative gate voltage is needed to produce the flat band condition. This is because there are positive surface charges in the oxide layer and a difference in the work functions of Semiconductor (Si) and metal (Al). Vfb is obtained from the gate voltage. Surface charge density and threshold voltage are obtained from Vfb.

Vfb is determined using flat band capacitance, Cfb, which is calculated from the following equation:

$$Cfb = \frac{Cox \cdot Csfb}{Cox + Csfb}$$

where Csfb is the depletion layer capacitance under flat band condition and is defined by the following equations:

$$Csfb = \frac{\sqrt{2} \cdot A \cdot \epsilon_0 \cdot \epsilon_{si}}{\lambda}$$

$$\lambda = \sqrt{\frac{2k \cdot T \cdot \epsilon_0 \cdot \epsilon_{si}}{q^2 \cdot Nsub}}$$

Using Nsub obtained in (1), we obtain the following:

$$Csfb = 9.615 \times 10^{-11} \ [F]$$
$$Cfb = 2.997 \times 10^{-11} \ [F]$$

Therefore Vfb is equal to −0.25 V.

(3) **Qss/q: Surface charge density**
In the oxide layer of a practical MOS device there is a fixed surface charge. Mobil ions and ionized traps make up the surface charge, so measured C-V characteristics differ from those of an ideal MOS. Since the surface charge depends on (i) the semiconductor orientation, (ii) oxidation, and (iii) annealing conditions, Qss is very important in the evaluation of wafer processes. The surface charge density is calculated from following equation:

$$\frac{Qss}{q} = \frac{Cox}{A \cdot q} |\Phi_{MS} - Vfb|$$

where ΦMS is the difference in the work functions of semiconductor (Si) and metal (Al). In this MOS diode, the following hold.

$$\phi f = -0.3061 \text{ V}$$
$$\Phi MS = -0.6 - \phi f = -0.2939 \text{V}$$

Therefore,

$$\frac{Qss}{q} = 1.193 \times 10^{10} \ [1/cm^3]$$

(4) **Vth: threshold voltage**
Vth is an important parameter in the analysis of MOSFET's Vth is defined by the following equation:

$$Vth = Vfb + (2\phi f - \frac{A \cdot Qb}{Cox})$$

where Qb is the fixed charge per unit area in the depletion layer and is defined as follows:

$$Qb = \pm q \cdot Nsub \cdot \frac{\epsilon_i \cdot \epsilon_{si} \cdot A}{Csmin} \begin{pmatrix} +: \text{n-type} \\ -: \text{p-type} \end{pmatrix}$$

In this MOS diode,

$$Qb = 1.690 \times 10^{-8} \ [coulomb/cm^2]$$

Therefore

$$Vth = -1.250 \text{ V}$$

3. C-t CHARACTERISTICS and ZERBST ANALYSIS

This chapter explains how to measure C-t characteristics of a MOS diode using the 4280A, and how to calculate $\tau geff$ and So from these characteristics.

$\tau geff$ (minority carrier lifetime in semiconductor bulk) and So (surface generation velocity) are very important parameters for evaluating the loss that occurs in charge-coupled devices (CCD) during charge transmission.

Measurement of $\tau geff$ and So is essential for the evaluation of Si wafers and for the study of new devices. Since $\tau geff$ and So are obtained by the Zerbst analysis of the C-t characteristics, these parameters can be calculated accurately using C-t data measured by the 4280A.

3.1 C-t Measurement

C-t characteristics of a MOS structure show the capacitance change after a pulse bias is applied which drives the structure first into accumulation then into deep inversion. Since the time constant of minority carrier generation is relatively long, the MOS structure requires time to reach equilibrium after the pulse bias is applied. Immediately after the pulse bias is applied, the depletion layer extends more widely then the depletion layer becomes narrower – the MOS structure approaches equilibrium as more and more minority carriers are generated. Finally, the depletion layer reaches its equilibrium width. This proves charge neutrality. The C-t characteristics are obtained from this change in the depletion layer width (Figure 3-1).

The HP 4280A offers two C-t measuring methods:

(1) using the 4280A's internal bias source as the pulse source (INT C-t), and

(2) using an external bias source (EXT C-t).

One of these methods is selected in accordance with the properties of the DUT and the measurement objectives.

(1) C-t Measurement Using the Internal Bias Source

In this mode, the measurement time interval (td) can be set from 10 ms to 32 s. To set up the C-t measurement, set the parameters Pulse V, Meas V, th, td, and NO OF RDNGS (number of measurements) as shown in Figure 3-1. When the sweep starts, PULSE V bias is applied to the DUT during th, then the bias changes to MEAS V. This changing point defines t = 0. Then measurements are made at intervals of td until the NO OF RDNGS is complete. Each measurement is made in the middle of the measurement interval.

The C-t measurements are sent to the X-Y recorder through the RECORDER OUTPUT. Using the HP-IB as shown in Figure 3-2, the C-t measurement and Zerbst analysis and plotting can be automated. This section describes C-t measurement as shown in Figure 3-2 (Page 21 shows a sample program.).

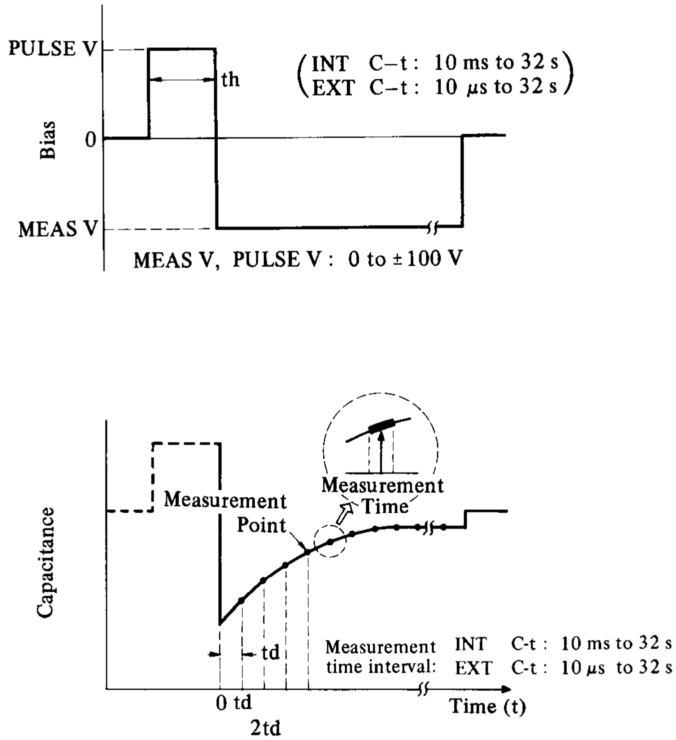


Figure 3-1 C-t Measurement

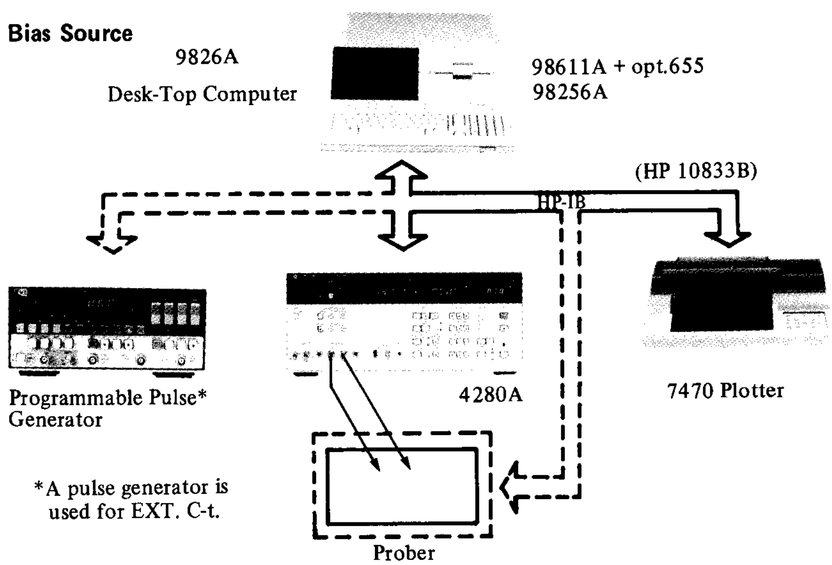


Figure 3-2 Example System for C-t Measurement and Zerbst Analysis

⟨ **Example of Measurement** ⟩

Figure 3-3 shows C-t characteristics for an n-type MOS diode measured under the following conditions:

PULSE V = 5 V
MEAS V = –5 V
NO OF RDNGS = 60
th = 5 s
td = 1 s

The MOS diode is forced into accumulation by applying a 5 V bias for 5 s then the bias is changed to –5 V. 60 measurements are then made at intervals of 1 s.

Figure 3-4 shows a graph of 100 C-t measurements that were taken at intervals of 10 ms using the block mode data output (see page 1).

Data with 4-digit resolution can be obtained with td as short as 10 ms (with opt. 001), so minute changes of capacitance can be resolved for accurate Zerbst analysis.

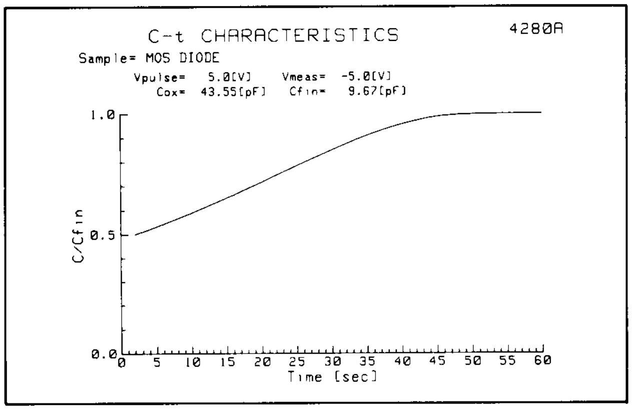


Figure 3-3 C-t Characteristics of a MOS Diode (INT C-t)

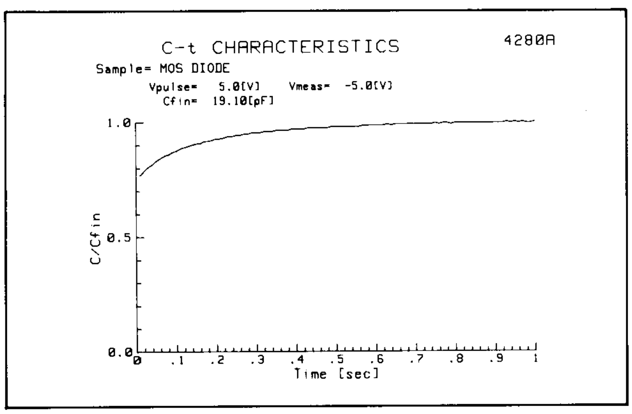


Figure 3-4 C-t Characteristics using the Block Mode (td = 10 ms)

(2) C-t Measurement Using an External Bias Source

By using a pulse generator with fast rise time, C-t characteristics with td ≧ 10 μs can be obtained.

Connect the OUTPUT terminal of the pulse generator to the EXT BIAS terminal (EXT SLOW or EXT FAST)* of the 4280A as shown in Figure 3-5. Also connect the pulse generator's EXT INPUT terminal to the 4280A's SYNC OUTPUT terminal.

Match the pulse width of the pulse generator to that of the 4280A so a pulse bias synchronized with 4280A can be applied to the DUT. If the pulse generator has an EXT WIDTH function, then the pulse bias width can be set equal to th. (The HP 8112A Programmable Pulse Generator has this function.)

*EXT SLOW: td ≧ 200 μs
EXT FAST: td ≧ 10 μs

⟨ **Example of Measurement** ⟩

In this example, an HP 8112A Programmable Pulse Generator is used as an external pulse bias source for measuring the C-t characteristics of a MOS diode. Set the 4280A and 8112A as follows:

- 4280A
  Measurement Function: C-t
  Measurement Speed: MED
  Connection Mode: CN13 (EXT FAST C-t)

  Parameter
  NO OF RDNGS: 50
  th: 1 ms
  td: 10 μs

- 8112A
  Mode: External width
  Output Levels: High = 2 V Low = –5 V
  Transition mode: Fastest transition (fixed)

Figure 3-6 shows C-t measurement results obtained under these test conditions. Even fast C-t characteristics can be measured reliably. Figure 3-7 shows the connections for EXT FAST C-t measurement (see page 15 for details about connection).

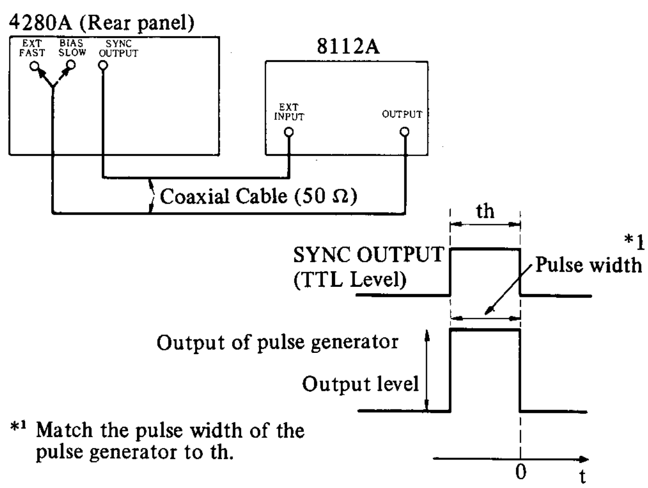


Figure 3-5 Connecting the 4280A to an External Bias Source

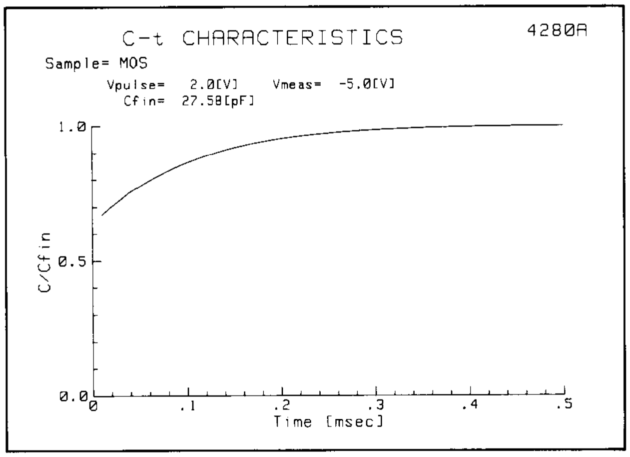


Figure 3-6 Measurement Results for a MOS Diode in the EXT C-t Mode (td = 10 μs)

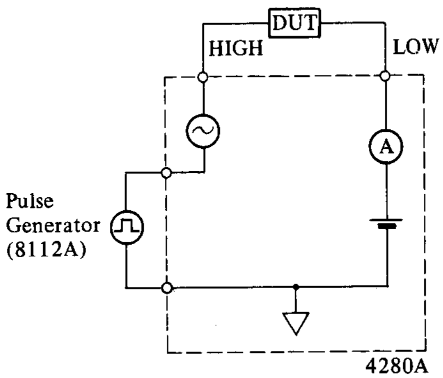


Figure 3-7 Connection Mode (CN13)

3.2 Zerbst Analysis

Figure 3-8 shows the Zerbst characteristics obtained by analyzing the C-t characteristics shown in Figure 3-3. The minority carrier lifetime, τgeff, and the surface generation velocity, So are calculated from Zerbst characteristics.

Zerbst characteristics can be obtained by plotting the following data.

$$\frac{\text{Cfin}}{\text{C}} - 1 \quad \text{VS} \quad -\frac{d}{dt}\left(\frac{\text{Cox}}{\text{C}}\right)^2$$

(X axis) (Y axis)

where

C is the measured capacitance, in Farads;
Cfin is the final (equilibrium) capacitance, in Farads;
Cox is the capacitance of the oxide layer, in Farads.

First, approximate the middle part of the Zerbst curve as a straight line and determine the slope (m) and the y-axis intercept (Δ). τgeff and So are obtained from the following equations:

$$\tau\text{geff} = 2 \cdot \frac{\text{ni}}{\text{Nsub}} \cdot \frac{\text{Cox}}{\text{Cfin}} \cdot \frac{1}{\text{m}} \qquad [\text{s}]$$

$$\text{So} = \frac{1}{2} \cdot \frac{\text{Nsub}}{\text{ni}} \cdot \frac{\epsilon_{si} \cdot \epsilon_0 \cdot \text{A}}{\text{Cox}} \cdot \Delta \qquad [\text{cm/s}]$$

Sampling Mode Measurement

High-resolution C-t measurement can be made in the sampling mode even when the measurement time interval (td) is as short as 10 μs.

This figure shows how the 4280A makes repeated measurements with a very short sampling at t = k$\cdot$td (k = 1, 2, . . .). Usually the sampling time ts is 1/5 of k$\cdot$td. Next the integrator circuit of the dual-slope A/D convertor of the 4280A is charged repeatedly (at each sample) until the total of ts reaches the integration time (tm) of an ordinary measurement method (such as the INT C-t measurement). The C (G)$\cdot$measurement is made with an resolution of 3 to 4 digits.

For example, when the measurement speed is FAST and td is 10 μs, at k = 1 (t = 10 μs),

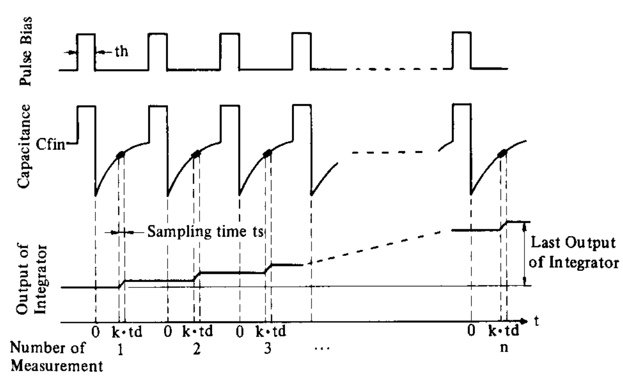
ts = 2 μs
Number of samples = 500

at k = 20 (t = 200 μs) then,

ts = 40 μs
Number of samples = 25

The number of samples decreases as t (= k $\cdot$ td) increases because the sampling time (ts) can be set larger as t increases. The number of samples is set automatically to the most suitable value for each measurement, t (= k$\cdot$td). This increases the efficiency of measurement, another advantage of this method.

The sampling mode permits measurement of even very fast C-t characteristics, so fast that they couldn't be measured until now. Even phenomena with very short time constants can be evaluated by the 4280A.



Measurement in the Sampling Mode (measurement time t = k$\cdot$td)

where

ni is the intrinsic carrier concentration, per cm^3;
Nsub is the impurity concentration in the substrate,
ϵ_{si} is the dielectric constant of Si (equals 11.7);
ϵ_0 is the permittivity of free space, (8.854×10^{-14} F/cm) and
A is the area of the gate, in cm^2.

From Figure 3-8 we obtain

$m \simeq 2.999,\ \Delta \simeq 0.2956$
$Cox = 43.55$ pF, $Cfin = 9.67$ pF,
$Nsub = 1.406 \times 10^{15}\ cm^3$ (See page 8.)

And also

$\tau geff = 1.625 \times 10^{-5}$ s
$So = 6.498 \times 10^{-1}$ cm/s
($T = 293$ K, $A = 0.001\ cm^2$)

A computer can be used with the HP 4280A to obtain τgeff and So more easily.

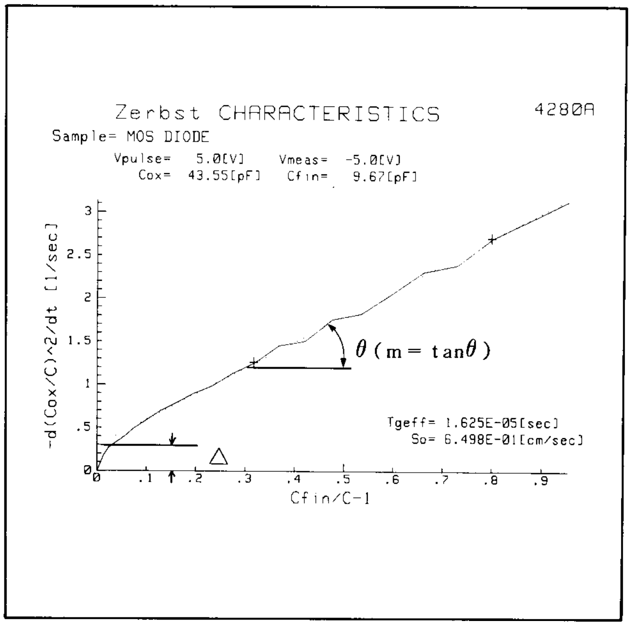


Figure 3-8 Zerbst Characteristics

4. DOPING PROFILE EVALUATION

The doping profile of a MOS structure can be obtained from C-V measurement results. The width of the depletion layer and the change in capacitance with applied bias voltage depend on doping concentration. The doping profile is calculated from the following equations:

$$N(W) = \frac{2}{q \cdot \epsilon_{si} \cdot \epsilon_0 \cdot A^2} \left[\frac{d}{dv} \left(\frac{1}{C^2} \right) \right]^{-1}$$

$$W = A \cdot \epsilon_{si} \cdot \epsilon_0 \left(\frac{1}{C} - \frac{1}{Cox} \right)$$

where

C is the measurement capacitance, in Farads; and
W is the depth, in cm.

The 4280A's internal dc bias can be set between −100 V to +100 V, so heavily doped substrates can be characterized. Reliability of results are enabled by the 4280A's high accuracy (best 0.1%) in measuring capacitance.

4. 1 Doping Profile Measurement

The 4280A can be used in any of three ways to make C-V measurements. In each method, the doping profile is computed from C-V data using an HP-IB controller.

(1) C-V measurement using ⌐ mode
(2) Pulsed C-V measurement
(Pulse bias is controlled by a computer program.)
(3) Pulse C-V measurement in C-t mode
(Pulse bias is controlled by a computer program.)

Method (1) uses C-V measurement as explained in chapter 2. The pulsed C-V techniques of (2) and (3) extend the depletion layer more deeply so that doping concentration is measured deeper in the substrate.

In method (2), the pulse bias is generated with the internal bias source in the (⎓) mode and measurements are made as shown in Figure 4-1. If the capacitance is measured in pulsed C-V measurement as soon as possible after pulse bias is applied and before the inversion layer is formed, then the doping profile can be evaluated deeper in the substrate. Thus, the shorter the bias settling time and measurement time are, the better.

The settling time of the interval bias source (99.9%) for the 4280A is about $(0.05 \cdot \Delta V + 1.7)$ ms (e.g. -5 V → 5 V takes about 2.2 ms). It takes about 15 ms to measure capacitance with 3-1/2-digit accuracy, so this measurement is usually made before the inversion layer forms.

If the inversion layer forms within several ms, method (3) is the best choice (pulsed C-V measurement in the EXT C-t mode). Set the parameters for EXT C-t measurement (refer to 3. 1) as follows:

i) th is the accumulation time (see Figure 4-1.)
ii) td is the wait time (see Figure 4-1.)
iii) NO OF RDNGS is set to 1.

This makes the pulsed C-V measurement possible in the EXT C-t mode, just as in method (2). The pulse bias level is set under HP-IB control. Using a pulse generator with fast rise time, the wait time and the measurement time can be shortened to 10 μs and 2 μs. (See page 11 for the EXT FAST C-t mode and td = 10 μs.) Therefore doping concentration can be measured deep in the substrate even in devices with fast responses.

Figure 4-2 shows the doping profile for a MOS diode obtained by method (2). In this measurement, the connection shown in Figure 2-3 is used.

Figure 4-3 shows the doping profile of a MOS diode measured under the following test conditions, using the system shown in Figure 4-4 and method (3).

- 4280A

  Measurement Function: C-t
  Measurement Speed: MED
  Connection Mode: CN13 (see the page 15)

  Parameters
  NO OF RDNGS: 1
  th: 2 ms
  td: 10 μs

- 8112A

  Mode: External width
  Output Level: Vacc, Vinv, and Bias step are set by HP-IB control (Figure 4-1 shows the Vacc, Vinv, and bias step.)

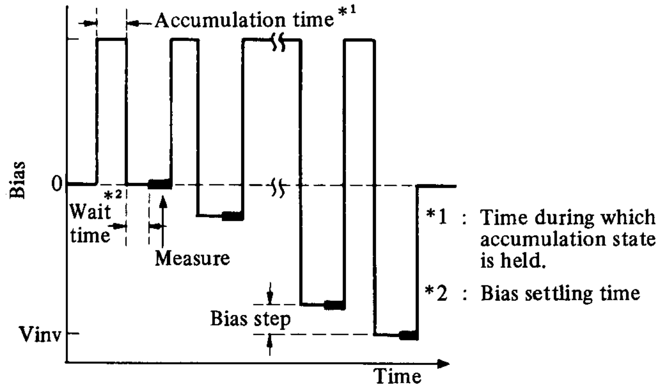


Figure 4-1 Pulsed C-V Measurement

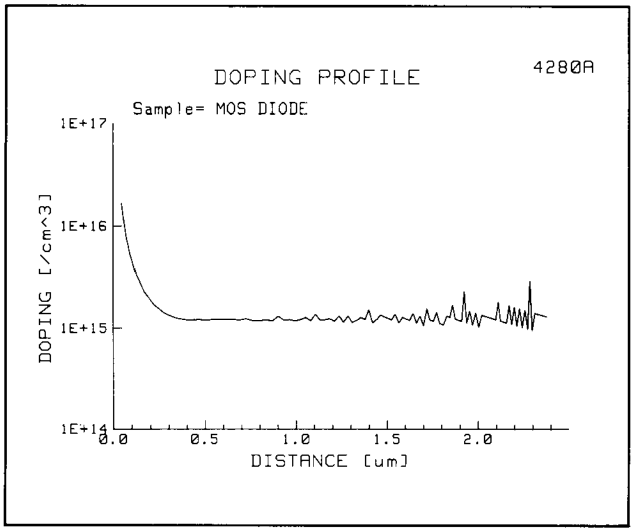


Figure 4-2 Doping Profile

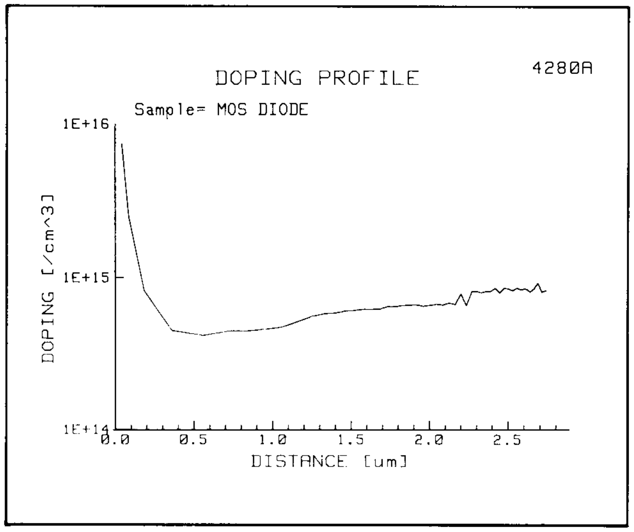


Figure 4-3 Doping Profile (EXT C-t Mode)

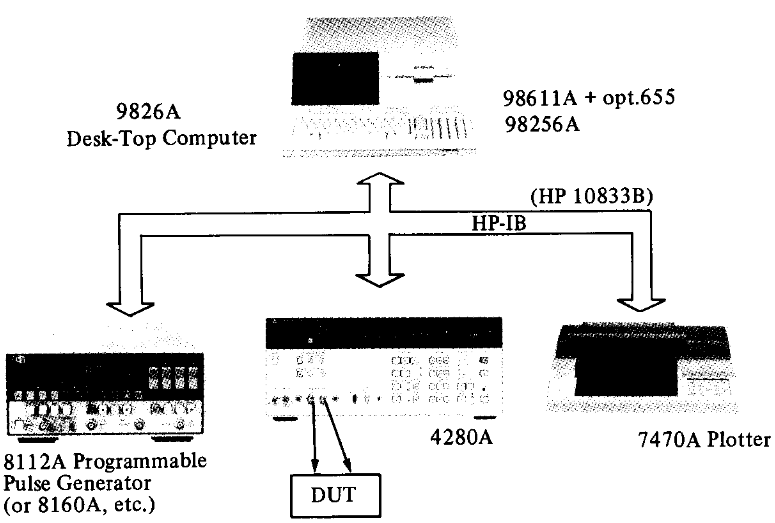


Figure 4-4 Example System for Doping Profile Measurement in the EXT C-t Mode

⟨Appendixes⟩

I. Evaluation of pn Junction Capacitance Characteristics

The pn junction is as important as MOS as a basic IC element. Many pn junction parameters, such as impurity concentration, and built-in potential, can be obtained from the C-V characteristics obtained by the HP4280A.

The following two models are valid for pn junctions.

(1) Abrupt pn Junctions
An abrupt pn junction is formed when the impurity concentration changes abruptly at the junction from acceptor impurities (N_A) to donor impurities (N_D). This is shown in Figure I-1. Especially, if $N_A \gg N_D$ (or $N_A \ll N_D$), then a one-sided abrupt junction, $p^+ - n$ (or $p - n^+$), is obtained.

(2) Linearly Graded pn Junctions
A linearly graded pn junction is formed when the impurity concentration changes linearly near the junction from N_A to N_D. Figure I-2 shows one example.

The abrupt junction is usual for shallow diffused pn junctions, and the linearly graded junction for deep diffused pn junctions. Also, the metal-semiconductor contact in a Schottky junction is identical to the one-sided abrupt junction using the abrupt approximation.

Table I-1 shows the theoretical equations describing C-V characteristics of each model and shows how to calculate parameters.

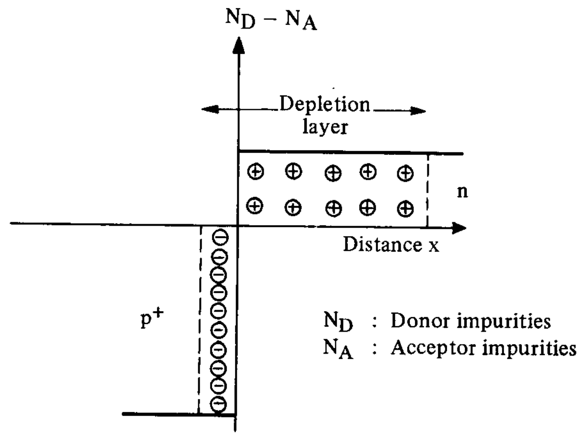


Figure I-1 The Abrupt pn Junction

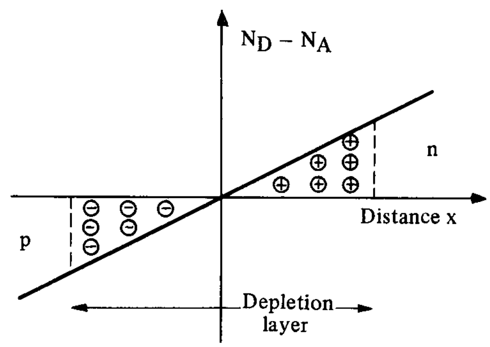


Figure I-2 The Linearly Graded pn Junction

		Abrupt pn Junction (one-sided)	Linearly Graded pn Junction
Theoretical Equation for C-V characteristics		$C = \sqrt{\dfrac{q \cdot \epsilon_s \cdot Nsub}{2\,(Vbi + V)}}$ per unit area or $\dfrac{1}{C^2} = \dfrac{2}{q \cdot \epsilon_s \cdot Nsub}\,(Vbi + V)$	$C = \left[\dfrac{q \cdot a \cdot \epsilon_s^2}{12\,(Vbi + V)}\right]^{1/3}$ per unit area or $\dfrac{1}{C^3} = \dfrac{12}{q \cdot a \cdot \epsilon_s^2}\,(Vbi + V)$
		where C is the capacitance of depletion layer, in Frads; V is the reverse bias, in Volts; Nsub is the impurity concentration of substrate per cm^3 (If $N_A \gg N_D$, then Nsub = N_D.); Vbi is the built-in in potential, in Volts; a is the impurity gradient, per cm^4; ϵ_s is the semiconductor permittivity, in Frads per cm; and q is the magnitude of electronic charge, in Coulombs.	
Parameters obtained from C-V Characteristics	Vbi Nsub or a	By graphing V (x-axis) vs $1/C^2$ (y-axis) $Nsub = \dfrac{2}{q \cdot \epsilon_s \cdot m}$ [$1/cm^3$] $Vbi = \dfrac{\Delta}{m}$ [V] where m is the slope, and Δ is the intercept of y-axis.	By graphing V (x-axis) vs $1/C^3$ (y-axis) $a = \dfrac{12}{q \cdot \epsilon_s^2 \cdot m}$ [$1/cm^4$] $Vbi = \dfrac{\Delta}{m}$ [V] where m is the slope, and Δ is the intercept of y-axis.
	Doping Profile	$N(W) = \dfrac{2}{q \cdot \epsilon_s \cdot A^2}\left[\dfrac{d}{dv}\left(\dfrac{1}{C^2}\right)\right]^{-1}$ [$1/cm^3$] $W = \dfrac{A \cdot \epsilon_s}{C}$ [cm] where A is the area of the gate in cm^2.	Cannot be determined from C-V characteristics.

Table I-1 Evaluation of pn Junction Capacitance

II. Connection Mode (CONN MODE)

4280A has 14 connection modes (CONN MODE), which are selected according to the DUT and measuring system.

(1) Connection Mode for Measurement of floating or grounded DUT using internal or external Bias Source

Figure II-1 (a) and (b) show the CONN MODE for measurement of floating DUT and grounded DUT using the internal bias source. Also, Figure II-2 shows CONN MODE for fast measurement of C-t characteristics. (EXT FAST C-t: measurement time interval, td $\geq 200\ \mu s$) using an external bias source (pulse generator) for both floating and grounded DUTs.

(2) Connection Mode for more accurate Measurement, using External Error Correction

Figure II-3 (a) shows the distribution of the stray admittances and residual impedances (due to probes, etc.) that exist in most measuring systems. Figure II-3 (b) is the equivalent circuit of (a). It is possible to measure the residual impedances using CONN MODE (CN21 to 23) then to eliminate residuals using a computer.

This will result in a more accurate measurement of the admittance of a DUT.

(3) Connection Mode for fast Measurement of C-t Characteristics

When very fast C-t characteristics are obtained, the measurement time interval td may be as short as $10\ \mu s$ (EXT FAST C-t). In this case, use CONN MODE CN13 (shown in Figure II-4), which bypasses the 4280A's filter circuit. This allows fast pulse bias to be applied and permits C-t measurement with td as short as $10\ \mu s$ to be performed.

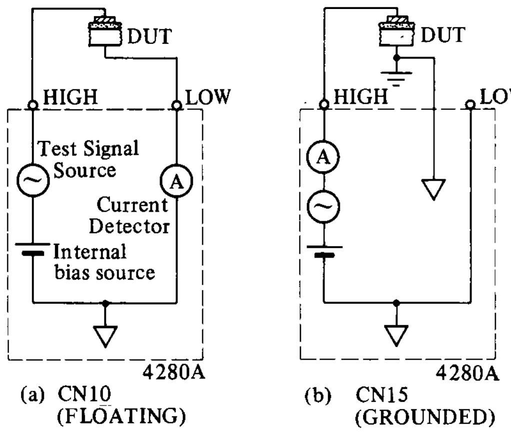


Figure II-1 Connection for Measurements on Floating and Grounded DUTs

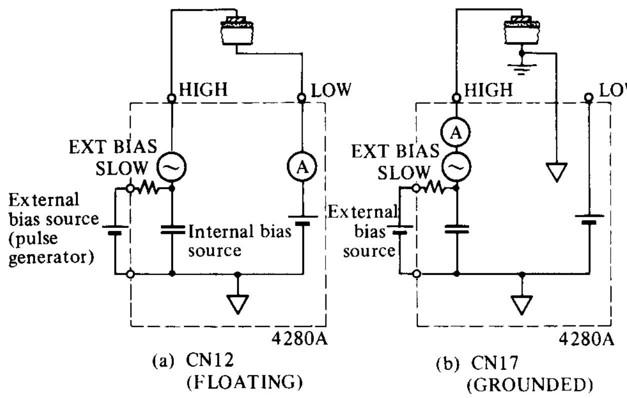


Figure II-2 Connection for EXT SLOW C-t Measurement (td $\geq 200\ \mu s$)

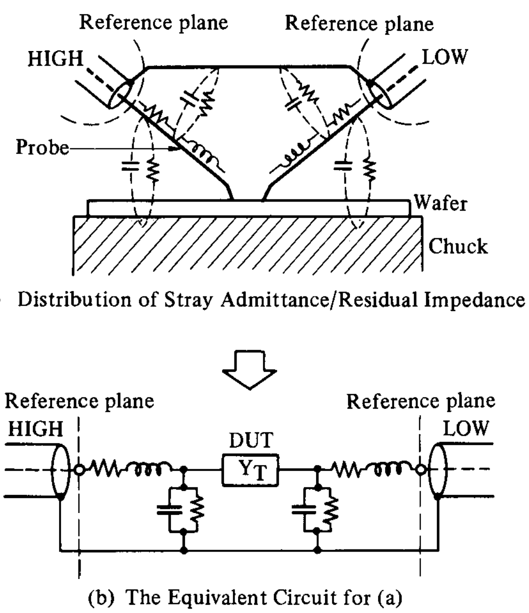


Figure II-3 Errors in a Measurement System

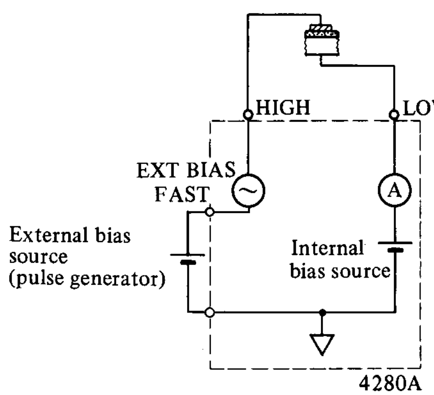


Figure II-4 Connection for EXT FAST C-t Measurement (CN13)

III. Sample Program

Shown below are flow chart (Figure III-1) and listings of the two programs that are used in this application note (Refer to 2.1 of page 6 and 3.1 (1) of page 9).

(1) Program for C-V characteristics measurement

(2) Program for C-t characteristics measurement

These programs must be run using the measurement systems shown in Figures 2-1 and 3-2 (a pulse generator is not needed).

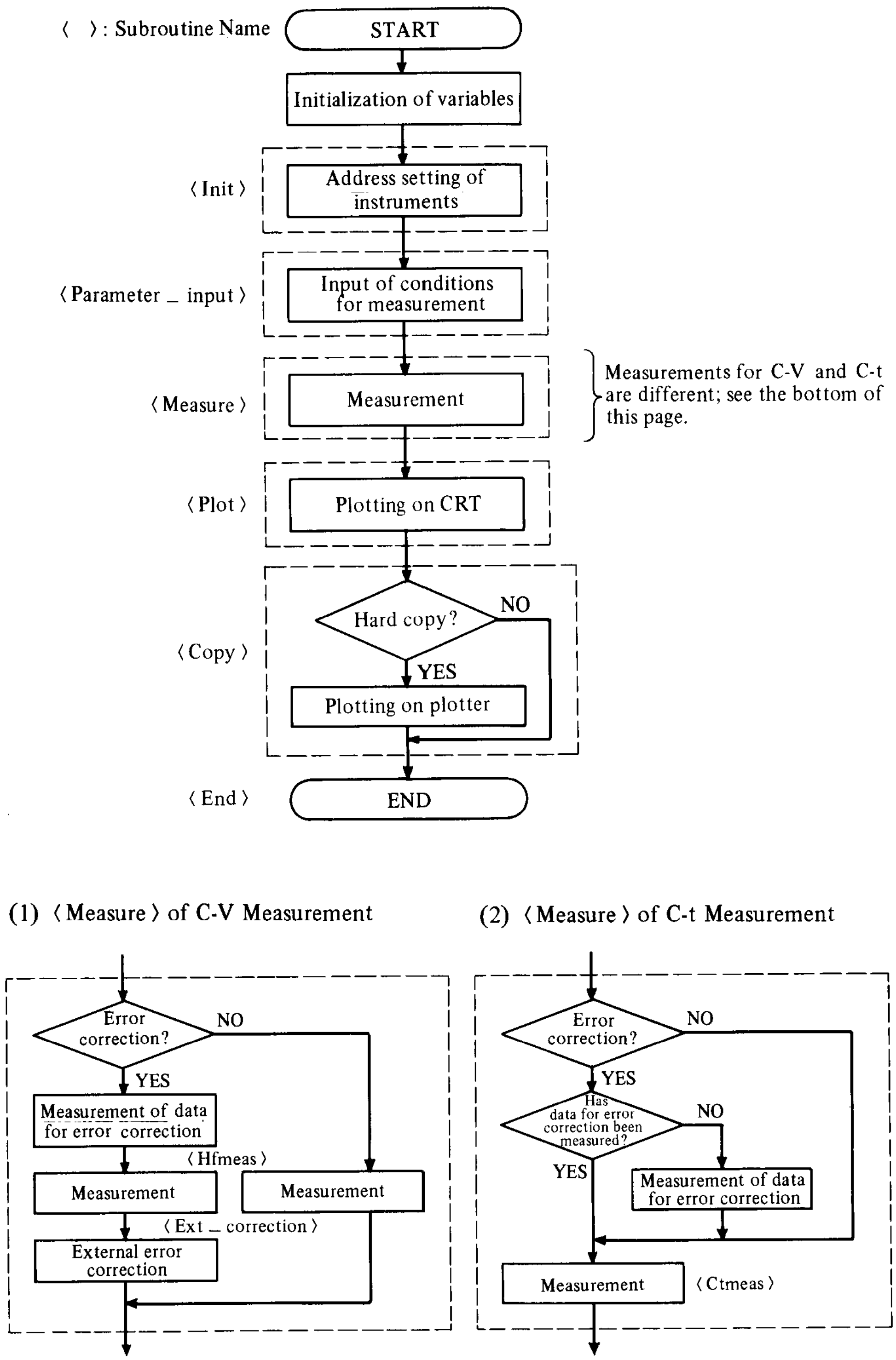


Figure III-1 Flow Chart of C-V/C-t Programs

(1) C-V Measurement Program

```
10    !    C-V MEASUREMENT   at 1MHz
20    !    BINARY FORMAT TRANSMISSION
30    OPTION BASE 1
40    DIM Bias(501),Val1(501),Val2(501),Val3(501)
50    DIM S(501),F$[100]
60    DIM Sample$[21]
70    !
80    GOSUB Init
90    GOSUB Parameter_input
100   GOSUB Measure
110   GOSUB Plot
120   GOSUB Copy
130   GOSUB End
140   !
150   ! ********** SUB(Init) ********************
160   !
170 Init:       !
180   PRINTER IS 1        ! CRT
190   S_code=7            ! SELECT CODE
200   Address_4280=17     ! 4280A ADDRESS
210   Cmeter80=S_code*100+Address_4280
220   RETURN
230   !
240   ! ********** SUB(Parameter_input) **********
250   !
260 Parameter_input:       !
270   BEEP
280   PRINT "ENTER THE FOLLOWING PARAMETERS.                    THEN PRESS CONT."
290   INPUT "START_V [V]      (-100 TO 100V)",Vstart
300   INPUT "STOP_V [V]       (-100 TO 100V)",Vstop
310   INPUT "STEP_V [V]       (0 TO 200V)",Vstep
320      Ndata=-INT(-ABS(Vstop-Vstart)/Vstep)+1
330      IF Ndata<=501 THEN 410
340      BEEP
350      DISP " NUMBER OF DATA EXCEEDS 501."
360      PAUSE
370      BEEP
380      DISP "INCREASE STEP_BIAS."
390      PAUSE
400      GOTO 310
410   INPUT "HOLD TIME [s]      (3ms TO 650s)",Hold_t
420   INPUT "STEP DELAY TIME [s]      (3ms TO 650s)",Delay_t
430   !
440    PRINT CHR$(12)
450    PRINT "START_V=";Vstart;"[V]"
460    PRINT "STOP_V=";Vstop;"[V]"
470    PRINT "STEP_V=";Vstep;"[V]"
480    PRINT "HOLD TIME=";Hold_t;"[s]"
490    PRINT "STEP DELAY TIME=";Delay_t;"[s]"
500    BEEP
510    INPUT "CHANGE SWEEP PARAMETERS ? (YES=1,NO=0)",Change
520    PRINT CHR$(12)
530    IF Change=1 THEN GOTO 270
540    !
550   INPUT "SELECT CABLE LENGTH (0m=0,1m=1,0-5m=2) ",Length
560    Length=Length+1
570   INPUT "AUTO or MANUAL RANGE ? (AUTO=1,MAN=0)",Range
580      IF Range=1 THEN Man=1
590      IF Range=0 THEN INPUT "SELECT RANGE (10pF=1,100pF=2,1nF=3) ",Man
600   INPUT "ERROR CORRECTION ? (YES=1,NO=0)",Zoff
610   RETURN
620   !
630   ! ********** SUB(Measure) ******************
640   !
650 Measure:        !
660   ! <<< CLEAR 4280A >>>
670   OUTPUT Cmeter80;"FN1,RA1,LE1,CE1,MS2,SL2,IB1,TR1"
680   OUTPUT Cmeter80;"SW0,V00,BL0,MD0,MA0,DC0,DG0,FL,AS,BC,IS0,TE0"
690   ! <<< ERROR CORRECTION >>>
700   IF Zoff=0 THEN GOTO 960
710   IF Length=3 THEN
720      BEEP
730      DISP "CONNECT NOTHING TO HIGH CABLE. THEN PRESS CONT."
740      PAUSE
750   !  Set(Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
760      CALL Set80(Cmeter80,Length,Man,Range,1,2,2,2,10)
770      OUTPUT Cmeter80;"TR3"
780      OUTPUT Cmeter80;"CA"
790      WAIT .5
800      ENTER Cmeter80;Yay1,Yax1
810      BEEP
820      DISP "CONNECT HIGH CABLE. THEN PRESS CONT."
830      PAUSE
840   END IF
850   !
860   BEEP
870   DISP "CONNECT NOTHING TO TEST FIXTURE. THEN PRESS CONT."
880   PAUSE
890   ! Set(Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
900   CALL Set80(Cmeter80,Length,Man,Range,1,2,2,2,10)
910   OUTPUT Cmeter80;"TR3"
920   OUTPUT Cmeter80;"Z0"
930   WAIT .5
940   ENTER Cmeter80;Zy1,Zx1
950   !
960   GOSUB Hfmeas
970   !
980   IF Zoff=1 THEN GOSUB Ext_correction
990   !
```

```
1000  Cmin=1.E+99
1010  Cox=0
1020  !
1030  FOR I=1 TO Ndata
1040    IF Val1(I)<Cmin THEN Cmin=Val1(I)
1050    IF Val1(I)>Cox THEN Cox=Val1(I)
1060  NEXT I
1070  RETURN
1080  !
1090  ! --- SUB(Hfmeas) --------------------------
1100  !
1110 Hfmeas:  !
1120  !
1130  BEEP
1140  DISP "CONNECT DUT. THEN PRESS CONT."
1150  PAUSE
1160  INPUT "ENTER SAMPLE NAME. (<20 Characters)",Sample$
1170  !
1180  ! <<< C-V/G-V MEASURE >>>
1190  ! Set(Cable,R_m,R_a,Func,M_s,S_1,Ibias,Conn)
1200  CALL Set80(Cmeter80,Length,Man,Range,1,2,2,2,10)
1210  !
1220  OUTPUT Cmeter80;"CE0,BN"
1230  !
1240  CALL Para80(Cmeter80,Vstart,Vstop,Vstep,Hold_t,Delay_t)
1250  !
1260  OUTPUT Cmeter80;"MF?"
1270  ENTER Cmeter80;F$
1280  Vstart=VAL(F$[POS(F$,"PS")+2])
1290  Vstop=VAL(F$[POS(F$,"PP")+2])
1300  Vstep=VAL(F$[POS(F$,"PE")+2])
1310  Ndata=-INT(-ABS(Vstop-Vstart)/Vstep)+1
1320  !
1330  CALL Sweep80(Cmeter80,3,1)
1340  !
1350  ! <<< DATA READING by BINARY FORMAT >>>
1360  DISP "MEASUREMENT IN PROGRESS"
1370  FOR I=1 TO Ndata
1380    ENTER Cmeter80 USING "#,B,W,W,W";S(I),Val1(I),Val2(I),Val3(I)
1390  NEXT I
1400  !
1410  ! <<< CONVERT DATA to ASCII FORMAT >>>
1420  FOR I=1 TO Ndata
1430  C_power=-12-2   ! pF + 2 digits shift
1440  G_power=-6-1    ! us + 1 digit shift
1450  !
1460    Power=BINAND(S(I),7)
1470    !
1480    IF Power=1 THEN
1490      GOTO 1640
1500    END IF
1510    !
1520    IF Power=2 THEN
1530      C_power=C_power+1
1540      G_power=G_power+1
1550      GOTO 1640
1560    END IF
1570    !
1580    IF Power=4 THEN
1590      C_power=C_power+2
1600      G_power=G_power+2
1610      GOTO 1640
1620    END IF
1630    !
1640    !
1650    IF BIT(S(I),3)=1 THEN  ! 10000 counts
1660      C_power=C_power-1
1670      G_power=G_power-1
1680    END IF
1690  !
1700    Val1(I)=Val1(I)*10^C_power
1710    Val2(I)=Val2(I)*10^G_power
1720  !
1730  NEXT I
1740  !
1750  IF Vstart>Vstop THEN Vstep=-Vstep
1760  !
1770  FOR I=1 TO Ndata
1780    Bias(I)=Vstart+(Val3(I)-1)*Vstep
1790  NEXT I
1800  IF ABS(Bias(Ndata))>ABS(Vstop) THEN Bias(Ndata)=Vstop
1810  !
1820  RETURN
1830  !
1840  ! --- SUB(Ext_correction) ------------------
1850 Ext_correction:  !
1860  IF Length=1 THEN          ! Length=0m
1870    P1x=1.002024
1880    P1y=-3.503999E-4
1890    Q1x=1.095
1900    Q1y=4.809150
1910    R1x=1.000001
1920    R1y=2.404563E-4
1930  END IF
1940  !
1950  IF Length=2 THEN          ! Length=1m
1960    P1x=1.006106
1970    P1y=-1.005985E-3
1980    Q1x=1.6312
1990    Q1y=8.298077
2000    R1x=1.000001
```

```
2010     R1y=4.166008E-4
2020   END IF
2030   !
2040   IF Length=3 THEN             ! Length=0-5m
2050       !
2060       Yax=Yax1
2070       Yay=Yay1*2*PI*1.E+6
2080       !
2090       Zox=2860.6381
2100       Zoy=-444.28789
2110       Yaxy=Yax*Yax-Yay*Yay
2120     P1x=1-Yaxy*Zox+2*Yax*Yay*Zoy
2130     P1y=-Yaxy*Zoy-2*Yax*Yay*Zox
2140     Q1x=2*(Zox*Yax-Zoy*Yay)+.283
2150     Q1y=2*(Zox*Yay+Zoy*Yax)
2160     R1x=1+.283*Yax
2170     R1y=.283*Yay
2180   END IF
2190   !
2200   Zx=Zx1
2210   Zy=Zy1*2*PI*1.E+6
2220   !
2230   W=2*PI*1.E+6
2240   !
2250   BEEP
2260   DISP "EXTERNAL ERROR CORRECTION IN PROGRESS"
2270   FOR I=1 TO Ndata
2280     Ymx=Val2(I)
2290     Ymy=Val1(I)*W
2300     A=R1x*Ymx-R1y*Ymy
2310     B=R1y*Ymx+R1x*Ymy
2320     C=P1x-(Q1x*Ymx-Q1y*Ymy)
2330     D=P1y-(Q1y*Ymx+Q1x*Ymy)
2340     Ccdd=C*C+D*D
2350     Ytx=(A*C+B*D)/Ccdd
2360     Yty=(B*C-A*D)/Ccdd
2370     !
2380     Val2(I)=Ytx-Zx
2390     Val1(I)=(Yty-Zy)/W
2400   NEXT I
2410   RETURN
2420   !
2430   ! ********** SUB(Plot) ********************
2440   !
2450 Plot:            !
2460   ALPHA OFF
2470   GCLEAR
2480   GINIT
2490   GRAPHICS ON
2500   !
2510   GOSUB Cv_plot
2520   RETURN
2530   !
2540   ! ********** SUB(Copy) ********************
2550 Copy:     !
2560   BEEP
2570   INPUT "NEED HARD COPY ? (YES=1,NO=0)",Cvcopy
2580   IF Cvcopy=1 THEN
2590         BEEP
2600         INPUT "ENTER PLOTTER ADDRESS.",Plotter
2610         BEEP
2620         DISP "PRESS CONT TO START THE PLOT."
2630         PAUSE
2640         Plotter=S_code*100+Plotter
2650         PLOTTER IS Plotter,"HPGL"
2660         GOSUB Cv_plot
2670         PENUP
2680   END IF
2690   RETURN
2700   !
2710   ! --- SUB(Cv_plot) ------------------------
2720 Cv_plot:     !
2730   FRAME
2740   VIEWPORT 16,130,10,78
2750   IF ABS(Vstop)>=ABS(Vstart) THEN Xmax1=INT(ABS(Vstop))
2760   IF ABS(Vstop)<ABS(Vstart) THEN Xmax1=INT(ABS(Vstart))
2770   IF (Xmax1 MOD 1)=0 THEN
2780     Xmax=Xmax1
2790   ELSE
2800     Xmax=Xmax1+1
2810   END IF
2820   ! <<< C-V PLOT >>>
2830   WINDOW -Xmax,Xmax,0,1
2840   AXES Xmax,.1,-Xmax,0,2,5,4
2850   MOVE Bias(1),Val1(1)/Cox
2860   FOR I=1 TO Ndata
2870     DRAW Bias(I),Val1(I)/Cox
2880   NEXT I
2890   LINE TYPE 6
2900   MOVE 0,0
2910   DRAW 0,1
2920   LINE TYPE 1
2930   !
2940   ! < X-AXIS >
2950   CLIP OFF
2960   CSIZE 4,.6
2970   LORG 6
2980   IF Xmax<=10 THEN Xstep=1
2990   IF (10<Xmax) AND (Xmax<=50) THEN Xstep=10
3000   IF (50<Xmax) AND (Xmax<=100) THEN Xstep=20
3010   FOR I=0 TO Xmax STEP Xstep
```

```
3020    MOVE I,-.005
3030    LABEL USING 3190;I
3040    CLIP ON
3050    DRAW I,.03
3060    MOVE I+Xstep/2,0
3070    DRAW I+Xstep/2,.015
3080    CLIP OFF
3090  NEXT I
3100  FOR I=0 TO -Xmax STEP -Xstep
3110    MOVE I,-.005
3120    LABEL USING 3190;I
3130    CLIP ON
3140    DRAW I,.03
3150    MOVE I-Xstep/2,0
3160    DRAW I-Xstep/2,.015
3170    CLIP OFF
3180  NEXT I
3190  IMAGE K
3200  ! < Y-AXIS >
3210  LORG 2
3220  FOR I=0 TO 1 STEP .5
3230    MOVE -Xmax*1.15,I
3240    LABEL USING 3250;I
3250    IMAGE Z.D
3260  NEXT I
3270  ! < X,Y-LABEL >
3280  CSIZE 5,.5
3290  MOVE 0,-.06
3300  LORG 6
3310  LABEL "BIAS [Volt]"
3320  !
3330  MOVE -Xmax*1.17,.5
3340  DEG
3350  LDIR 90
3360  LORG 4
3370  LABEL "C/Cox"
3380  LDIR 0
3390  !
3400  ! <<< LABELING >>>
3410  VIEWPORT 0,140,0,100
3420  WINDOW 0,140,0,100
3430  MOVE 130,95
3440  CSIZE 5,.6
3450  LORG 4
3460  LABEL "4280A"
3470  MOVE 70,93
3480  CSIZE 6,.6
3490  LORG 4
3500  LABEL "C-V CHARACTERISTICS"
3510  MOVE 5,85
3520  CSIZE 4.5,.5
3530  LORG 1
3540  LABEL "Sample= "&Sample$
3550  MOVE 10,80
3560  LABEL USING 3570;Cox*1.E+12
3570  IMAGE "Cox= ",3D.2D," [pF]"
3580  RETURN
3590  !
3600  ! ********** SUB(End) *********************
3610 End:    !
3620  DISP "             END              "
3630  PAUSE
3640  END
3650  !
3660  ! -----------------------------------------
3670  ! ---------- SUB PROGRAM -------------------
3680  ! -----------------------------------------
3690  ! *** SUB(Para80) *************************
3700  !
3710  SUB Para80(Cmeter80,Vstart,Vstop,Vstep,Hold_t,Delay_t)
3720  OUTPUT Cmeter80;"PS";Vstart
3730  OUTPUT Cmeter80;"PP";Vstop
3740  OUTPUT Cmeter80;"PE";Vstep
3750  OUTPUT Cmeter80;"PL";Hold_t
3760  OUTPUT Cmeter80;"PD";Delay_t
3770  SUBEND
3780  !
3790  ! *** SUB(Set80) **************************
3800  !
3810  SUB Set80(Cmeter80,Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
3820  OUTPUT Cmeter80 USING 3830;Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn
3830  IMAGE "LE",D,"RM",D,"RA",D,"FN",D,"MS",D,"SL",D,"IB",D,"CN",DD
3840  SUBEND
3850  !
3860  ! *** SUB(Sweep80) ************************
3870  !
3880  SUB Sweep80(Cmeter80,Mode,Sweep)
3890  OUTPUT Cmeter80;"BC"
3900  OUTPUT Cmeter80 USING 3910;Mode,Sweep
3910  IMAGE "TR",D,"SW",D
3920  SUBEND
3930  !
3940  ! *** SUB(Bias80) *************************
3950  !
3960  SUB Bias80(Cmeter80,Dcv)
3970  OUTPUT Cmeter80 USING 3980;Dcv
3980  IMAGE "PV",SD.3DE
3990  OUTPUT Cmeter80;"V01"
4000  SUBEND
4010  !
```

(2) C-t Measurement Program

```
10    !     C-t MEASUREMENT
20    !     BLOCK MODE
30    OPTION BASE 1
40    DIM Val1(680),T(680)
50    DIM Sample$[21]
60    COM Data_ready,Cmeter80,S_code
70    !
80    GOSUB Init
90    GOSUB Parameter_input
100   GOSUB Measure
110   GOSUB Plot
120   GOSUB Copy
130   GOSUB End
140   !
150   ! ********** SUB(Init) ********************
160 Init:  !
170   PRINTER IS 1        ! CRT
180   S_code=7            ! SELECT CODE
190   Address_4280=17   ! 4280A ADDRESS
200   Cmeter80=S_code*100+Address_4280
210   RETURN
220   !
230   ! ********** SUB(Parameter_input) **********
240 Parameter_input:  !
250   BEEP
260   PRINT "ENTER THE FOLLOWING PARAMETERS.                    THEN PRESS CONT."
270   INPUT "PULSE_V [V]     (-100 TO +100V)",Pulsev
280   INPUT "MEAS_V [V]     (-100 TO +100V)",Measv
290   INPUT "NO OF READINGS     (1 TO 680)",Nread
300   INPUT "th [s]     (10ms TO 32s)",Th
310   INPUT "td [s]     (10ms TO 32s)",Td
320   !
330    PRINT CHR$(12)
340    PRINT "PULSE_V=";Pulsev;" [V]"
350    PRINT "MEAS_V=";Measv;" [V]"
360    PRINT "NO OF READINGS=";Nread
370    PRINT "th=";Th;" [s]"
380    PRINT "td=";Td;" [s]"
390    BEEP
400    INPUT "CHANGE SWEEP PARAMETERS ? (YES=1,NO=0)",Change
410    PRINT CHR$(12)
420    IF Change=1 THEN GOTO 250
430   INPUT "SELECT CABLE LENGTH (0m=0,1m=1,0-5m=2)",Length
440    Length=Length+1
450   INPUT "AUTO or MANUAL RANGE ? (AUTO=1,MAN=0)",Range
460      IF Range=1 THEN Man=1
470      IF Range=0 THEN INPUT "SELECT RANGE (10pF=1,100pF=2,1nF=3)",Man
480   INPUT "ENTER Cox [pF].",Cox1
490      Cox1=Cox1*1.E-12        ! [F]
500   INPUT "ERROR CORRECTION ? (YES=1,NO=0)",Zoff
510   RETURN
520   !
530   ! ********** SUB(Measure) ******************
540 Measure:  !
550   !
560   ! <<< CLEAR 4280A >>>
570   OUTPUT Cmeter80;"FN1,RA1,LE1,CE1,MS2,SL2,IB1,TR1"
580   OUTPUT Cmeter80;"SW0,V00,BL0,MD0,MA0,DC0,DG0,FL,AS,BC,IS0,TE0"
590   !
600   ! <<< ERROR CORRECTION >>>
610   IF Zoff=0 THEN GOTO 890
620   IF Zoff=1 THEN
630     BEEP
640     IF Length=1 OR Length=2 THEN INPUT "HAS Z_OPEN BEEN PERFORMED ? (YES=1,N
O=0)",Correct
650     IF Length=3 THEN INPUT "HAS C_CAL & Z_OPEN BEEN PERFORMED ? (YES=1,NO=0)
",Correct
660   END IF
670   IF Correct=1 THEN GOTO 890
680   IF Length=3 THEN
690     BEEP
700     DISP "CONNECT NOTHING TO HIGH CABLE. THEN PRESS CONT."
710     PAUSE
720   ! Set(Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
730     CALL Set80(Cmeter80,Length,Man,Range,5,1,2,2,10)
740     OUTPUT Cmeter80;"TR3"
750     OUTPUT Cmeter80;"CA"
760     BEEP
770     DISP "CONNECT HIGH CABLE.  THEN PRESS CONT."
780     PAUSE
790   END IF
800   !
810   BEEP
820   DISP "CONNECT NOTHING TO TEST FIXTURE. THEN PRESS CONT."
830   PAUSE
840   ! Set(Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
850   CALL Set80(Cmeter80,Length,Man,Range,5,1,2,2,10)
860   OUTPUT Cmeter80;"TR3"
870   OUTPUT Cmeter80;"Z0"
880   !
890   GOSUB Ctmeas
900   RETURN
910   !
920   ! --- SUB(Ctmeas) --------------------------
930   !
940 Ctmeas:   !
950   !
960   BEEP
970   DISP "CONNECT DUT. THEN PRESS CONT."
```

```
980    PAUSE
990    INPUT "ENTER SAMPLE NAME. (<20 Characters)",Sample$
1000   !
1010   ! <<< Enable Interrupt >>>
1020   ON INTR S_code,15 CALL Ready
1030   !
1040   ! <<< Cox Measure >>>
1050   IF Cox1=0 THEN
1060     ! Set(Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
1070     CALL Set80(Cmeter80,Length,Man,1,1,2,2,1,10)
1080     OUTPUT Cmeter80;"TR3"
1090     CALL Bias80(Cmeter80,Pulsev)
1100     WAIT Th
1110     TRIGGER Cmeter80
1120     WAIT .1
1130     ENTER Cmeter80;Cox1
1140     OUTPUT Cmeter80;"V00"
1150   END IF
1160   Cox=Cox1
1170   !
1180   ! <<< C-t Measure >>>
1190   ! Set(Cable,R_m,R_a,Func,M_s,S_l,Ibias,Conn)
1200   CALL Set80(Cmeter80,Length,Man,Range,5,1,2,2,10)
1210   IF Zoff=0 THEN OUTPUT Cmeter80;"CE0"
1220   IF Zoff=1 THEN OUTPUT Cmeter80;"CE1"
1230   !
1240   ! < Ranging >
1250   ! If the Range is AUTO and td<=100ms,then---
1260   IF Range=1 AND Td<=.1 THEN
1270     CALL Para801(Cmeter80,Pulsev,Measv,1,Th,Td)
1280     OUTPUT Cmeter80;"BL1"
1290     OUTPUT Cmeter80;"MD1"
1300     ENABLE INTR S_code;2
1310     CALL Sweep80(Cmeter80,3,1)
1320     Data_ready=0
1330 Wait:  IF Data_ready=0 THEN GOTO Wait
1340     OUTPUT Cmeter80;"RA0"
1350     OUTPUT Cmeter80;"BL0"
1360   END IF
1370   !
1380   ! < Measure >
1390   CALL Para801(Cmeter80,Pulsev,Measv,Nread,Th,Td)
1400   !
1410   OUTPUT Cmeter80;"BL1"
1420   OUTPUT Cmeter80;"MD1"
1430   ENABLE INTR S_code;2
1440   CALL Sweep80(Cmeter80,3,1)
1450   !
1460   Data_ready=0
1470   DISP "MEASUREMENT IN PROGRESS"
1480   !
1490 Wait1: IF Data_ready=0 THEN GOTO Wait1
1500   !
1510   BEEP
1520   DISP "DATA READING IN PROGRESS"
1530   OUTPUT Cmeter80;"BD"
1540   FOR I=1 TO Nread
1550     CALL Read801(Cmeter80,Valx,T1)
1560     Val1(I)=Valx
1570     T(I)=T1
1580   NEXT I
1590   !
1600   Cfin=Val1(Nread)
1610   BEEP
1620   BEEP
1630   OUTPUT Cmeter80;"BL0,MD0"
1640   RETURN
1650   !
1660   ! ********** SUB(Plot) ********************
1670 Plot: !
1680   ALPHA OFF
1690   GCLEAR
1700   GINIT
1710   GRAPHICS ON
1720   !
1730   GOSUB Ct_plot
1740   RETURN
1750   !
1760   ! ********** SUB (Copy) *******************
1770 Copy:    !
1780   BEEP
1790   INPUT "NEED HARD COPY ? (YES=1,NO=0)",Ctcopy
1800   IF Ctcopy=1 THEN
1810         BEEP
1820         INPUT "ENTER PLOTTER ADDRESS.",Plotter
1830         BEEP
1840         DISP "PRESS CONT TO START THE PLOT."
1850         PAUSE
1860         Plotter=S_code*100+Plotter
1870         PLOTTER IS Plotter,"HPGL"
1880         GOSUB Ct_plot
1890         PENUP
1900   END IF
1910   RETURN
1920   !
1930   ! --- SUB (Ct_plot) ------------------------
1940 Ct_plot:    !
1950   FRAME
1960   VIEWPORT 16,130,10,75
1970   Xmax=Td*Nread
1980   ! <<< C-t PLOT >>>
```

```
1990  WINDOW 0,Xmax,0,1
2000  IF Xmax>60 THEN AXES 10,.1,0,0,3,5,4
2010  IF (5<Xmax) AND (Xmax<=60) THEN AXES 1,.1,0,0,5,5,4
2020  IF (1<Xmax) AND (Xmax<=5) THEN AXES .1,.1,0,0,5,5,4
2030  IF Xmax<=1 THEN AXES .02,.1,0,0,5,5,4
2040  MOVE T(1),Val1(1)/Cfin
2050  FOR I=1 TO Nread
2060    DRAW T(I),Val1(I)/Cfin
2070  NEXT I
2080  !
2090  ! < X-AXIS >
2100  CLIP OFF
2110  CSIZE 4,.6
2120  LORG 6
2130  IF Xmax>60 THEN Xstep=30
2140  IF (5<Xmax) AND (Xmax<=60) THEN Xstep=5
2150  IF (1<Xmax) AND (Xmax<=5) THEN Xstep=.5
2160  IF Xmax<=1 THEN Xstep=.1
2170  FOR I=0 TO Xmax STEP Xstep
2180    MOVE I,-.005
2190    IF Xmax>60 THEN
2200      LABEL USING 2240;I/60
2210    ELSE
2220      LABEL USING 2240;I
2230    END IF
2240    IMAGE K
2250  NEXT I
2260  ! < Y-AXIS >
2270  LORG 8
2280  FOR I=0 TO 1 STEP .5
2290  MOVE -Xmax*.01,I
2300  LABEL USING 2310;I
2310  IMAGE Z.D
2320  NEXT I
2330  ! < X,Y-LABEL >
2340  CSIZE 5,.5
2350  MOVE Xmax/2,-.06
2360  LORG 6
2370  IF Xmax>60 THEN LABEL "Time [min]"
2380  IF Xmax<=60 THEN LABEL "Time [sec]"
2390  MOVE -Xmax*.08,.5
2400  DEG
2410  LDIR 90
2420  LORG 4
2430  LABEL "C/Cfin"
2440  LDIR 0
2450  !
2460  ! <<< LABELING >>>
2470  VIEWPORT 0,140,0,100
2480  WINDOW 0,140,0,100
2490  MOVE 130,95
2500  CSIZE 5,.6
2510  LORG 4
2520  LABEL "4280A"
2530  MOVE 60,93
2540  CSIZE 6,.6
2550  LORG 4
2560  LABEL "C-t CHARACTERISTICS "
2570  MOVE 5,88
2580  CSIZE 4.5,.5
2590  LORG 1
2600  LABEL "Sample= "&Sample$
2610  MOVE 20,83
2620  CSIZE 4,.5
2630  LORG 1
2640  LABEL USING 2660;Pulsev,Measv
2650  LABEL USING 2670;Cox*1.E+12,Cfin*1.E+12
2660  IMAGE "Vpulse= ",3D.D,"[V]",4X,"Vmeas= ",3D.D,"[V]"
2670  IMAGE "    Cox= ",3D.2D,"[pF]",X,"  Cfin= ",3D.2D,"[pF]"
2680  RETURN
2690  !
2700  ! ********** SUB(End) **********************
2710 End:   !
2720  DISP "              END                    "
2730  PAUSE
2740  END
2750  !
2760  ! ------------------------------------------
2770  ! ---------- SUB PROGRAM -------------------
2780  ! ------------------------------------------
2790  ! *** SUB(Para801) ************************
2800  !
2810  SUB Para801(Cmeter80,Pulsev,Measv,Nread,Th,Td)
2820  OUTPUT Cmeter80;"PU";Pulsev
2830  OUTPUT Cmeter80;"PM";Measv
2840  OUTPUT Cmeter80;"PN";Nread
2850  OUTPUT Cmeter80;"PH";Th
2860  OUTPUT Cmeter80;"PT";Td
2870  SUBEND
2880  !
2890  ! *** SUB(Set80) ***************************
2900  !
2910  SUB Set80(Cmeter80,Cable,R_m,R_a,Func,M_s,S_1,Ibias,Conn)
2920  OUTPUT Cmeter80 USING 2930;Cable,R_m,R_a,Func,M_s,S_1,Ibias,Conn
2930  IMAGE "LE",D,"RM",D,"RA",D,"FN",D,"MS",D,"SL",D,"IB",D,"CN",DD
2940  SUBEND
2950  !
2960  ! *** SUB(Sweep80) ************************
2970  !
2980  SUB Sweep80(Cmeter80,Mode,Sweep)
2990  OUTPUT Cmeter80;"BC"
```

```
3000  OUTPUT Cmeter80 USING 3010;Mode,Sweep
3010  IMAGE "TR",D,"SW",D
3020  SUBEND
3030  ! *** SUB(Bias80) **************************
3040  !
3050  SUB Bias80(Cmeter80,Dcv)
3060  OUTPUT Cmeter80 USING 3070;Dcv
3070  IMAGE "PV",SD.3DE
3080  OUTPUT Cmeter80;"V01"
3090  SUBEND
3100  !
3110  ! *** SUB(Read801) *************************
3120  !
3130  SUB Read801(Cmeter80,Aval,Bval)
3140  ENTER Cmeter80;Aval,Bval
3150  SUBEND
3160  !
3170  ! *** SUB(Ready) **************************
3180  !
3190  SUB Ready
3200  COM Data_ready,Cmeter80,S_code
3210  STATUS S_code;Aa
3220  P=SPOLL(Cmeter80)
3230  IF BIT(Aa,0)=0 THEN GOTO Not_data_ready
3240  Data_ready=1
3250  WAIT .1
3260 Not_data_ready:    !
3270  SUBEND
```

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