

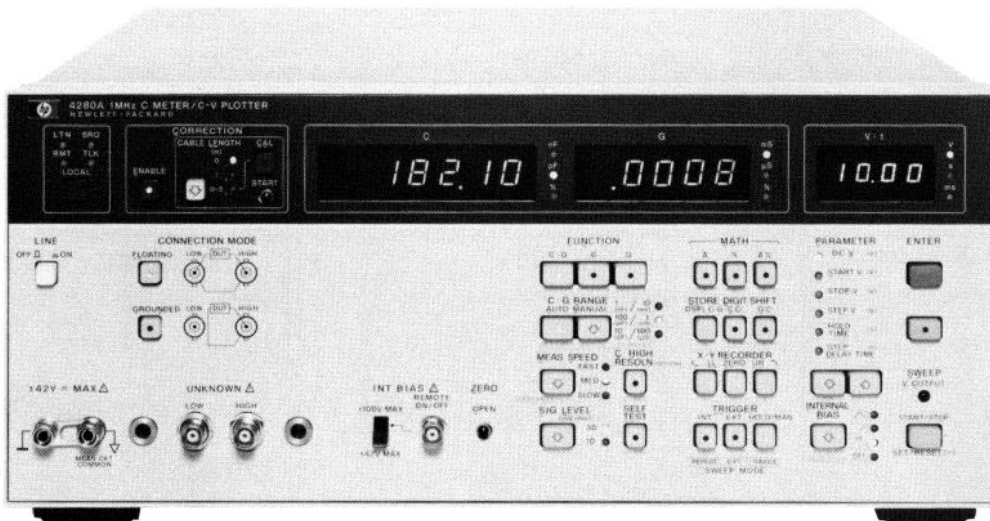
# Analysis of Semiconductor Capacitance Characteristics

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



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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 measure-

ment 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 data 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 transferred 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 ( $V_{fb}$ ), and threshold voltage ( $V_{th}$ ) 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 ( $C_{ox}$ ) and depletion-layer capacitance ( $C_d$ ). Total capacitance is obtained from the equation below:

$$C = \frac{C_{ox} \cdot C_d}{C_{ox} + C_d}$$

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<sub>2</sub> surface. In this state,  $C_d$  is negligible and MOS capacitance is equal to  $C_{ox}$ , 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<sub>2</sub> surface. Donor ions remain as fixed charges, forming the depletion layer. In this state, MOS capacitance consists of  $C_{ox}$  and  $C_d$ , which varies with the applied gate voltage. The MOS capacitance is calculated from this equation:

$$C = \frac{C_{ox} \cdot C_d}{C_{ox} + C_d}$$

#### (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  $C_{ox}$ , 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).

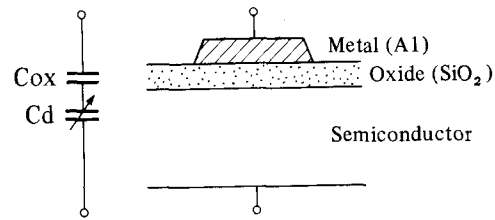


Figure 1-1 MOS Structure

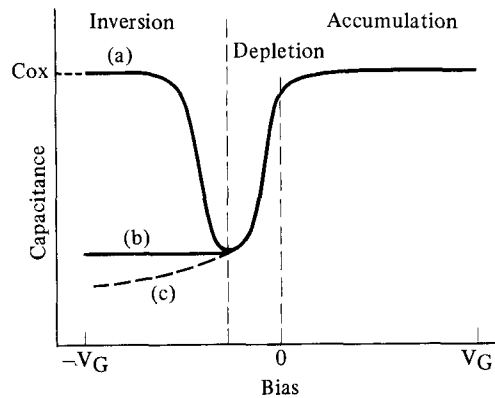


Figure 1-2 C-V Characteristics of a MOS Structure

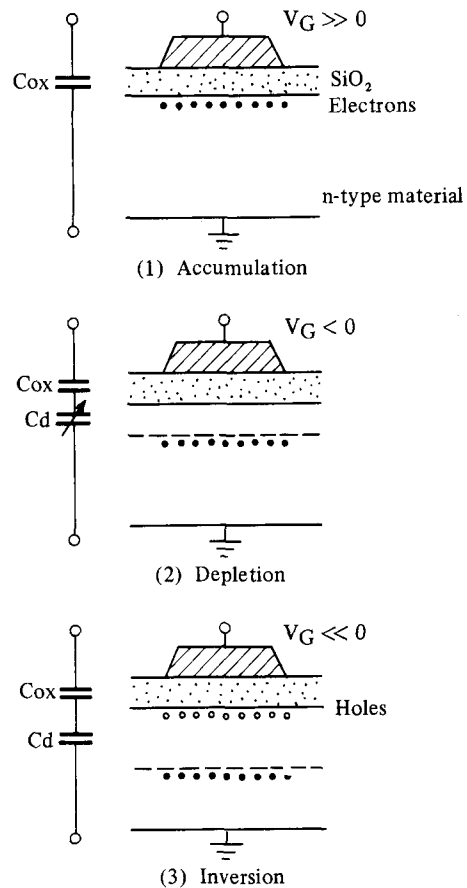


Figure 1-3 Carrier Distribution of a MOS Structure

### ■ 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,  $C_d$ , depends on the applied bias voltage. Because  $C_d$  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.

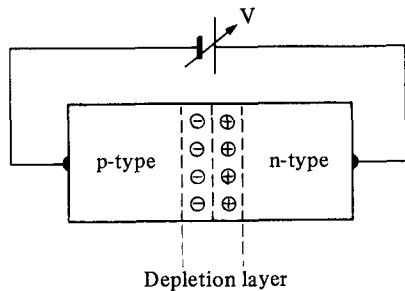


Figure 1-4 pn Junction

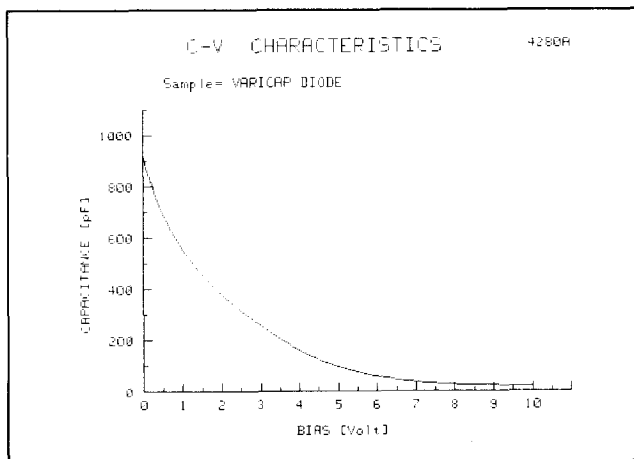


Figure 1-5 C-V Characteristics of a pn Junction

## 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).

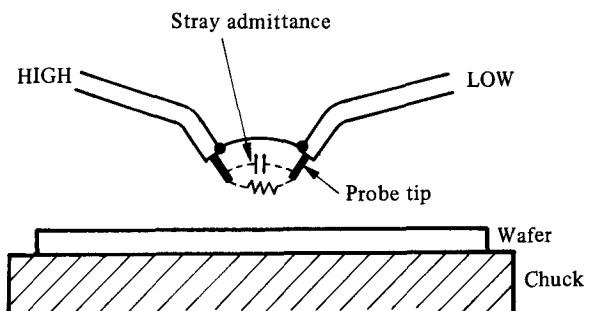
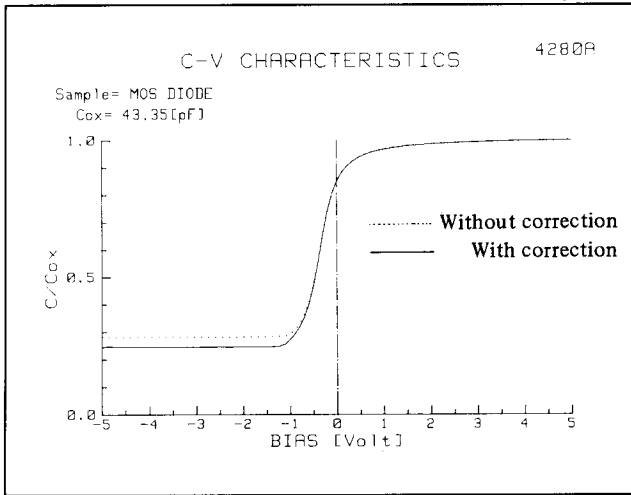


Figure 1-6 Open Condition



**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**

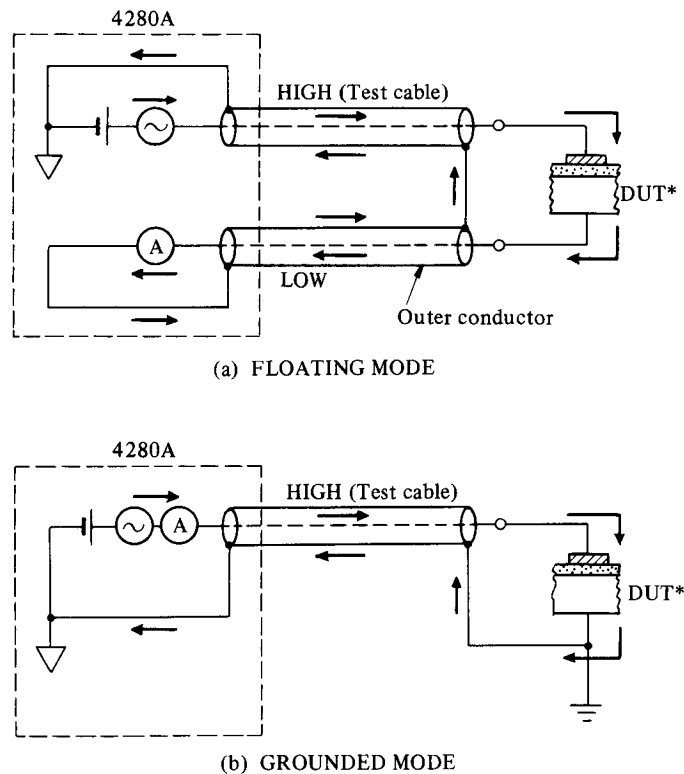
Figure 1-8 illustrates the two-terminal pair measurement method. When using a coaxial cable in this method, currents of equal and opposite direction flow down the

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**

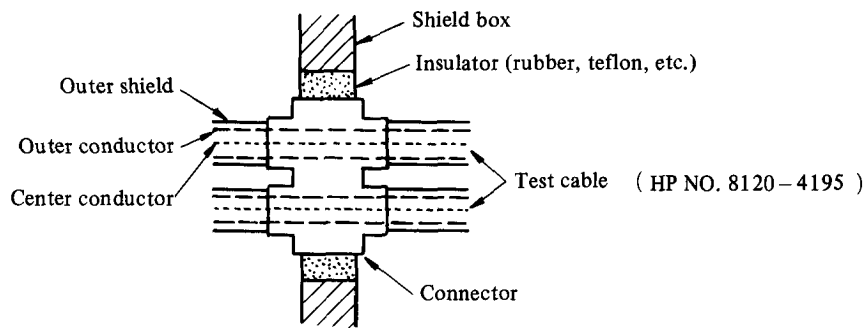
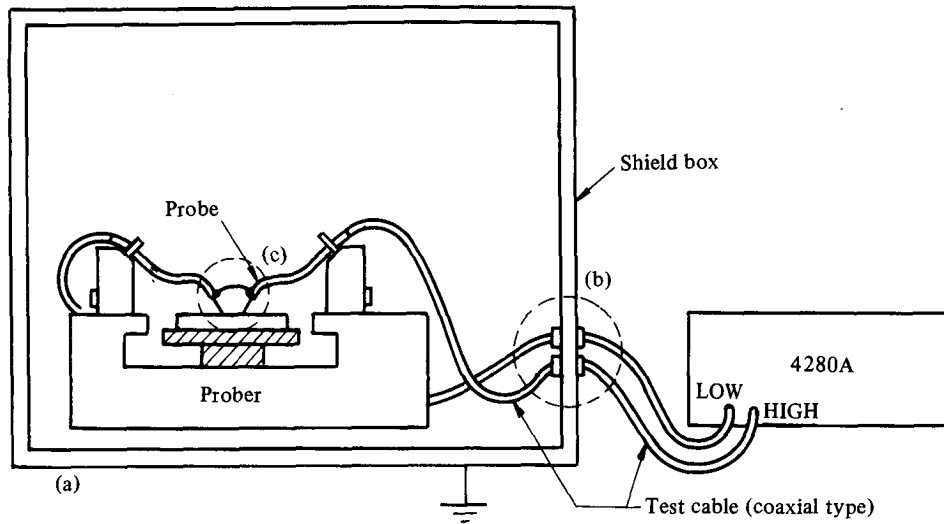
When the device under test is grounded (for example, the chuck of a wafer prober), select the "GROUNDED" CONNECTION MODE. In the grounded mode, the current flowing in the DUT is measured correctly and noise from ground is eliminated. This improves measurement accuracy. The grounded measurement is performed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

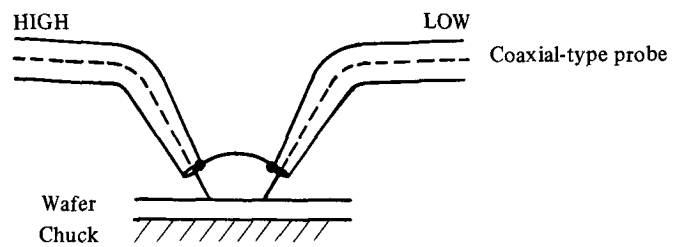


\*DUT: Device Under Test

**Figure 1-8** Two-Terminal Pair Measurement Method



(b) Enlargement of the connector



(c) Enlargement of the probe end

**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 ( $C_{ox}$ ) before the sweep.  $C_{ox}$  is then used as the normalization constant and the 4280A's math function is used to plot  $C/C_{ox}$ .

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 Measurement >

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 = 10s  
 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.)

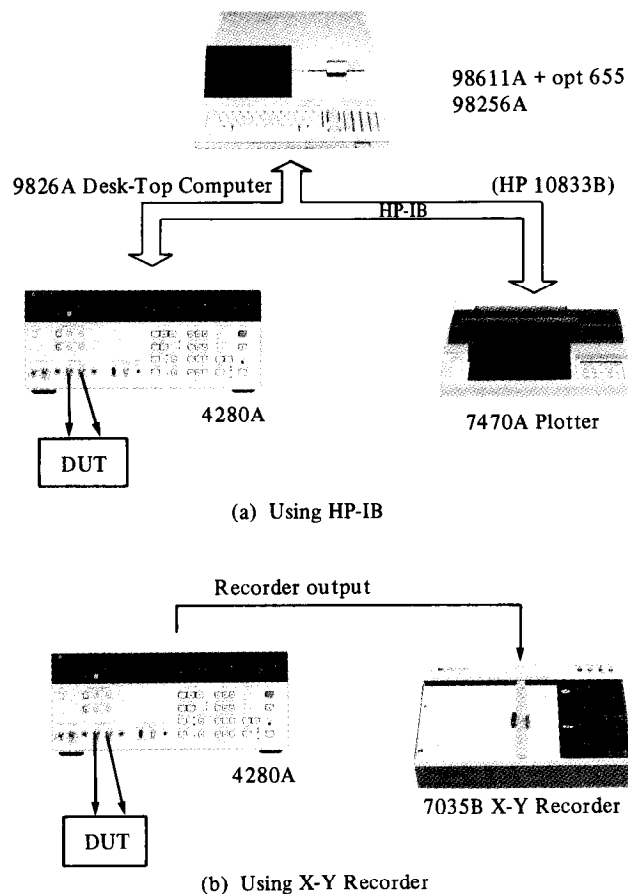


Figure 2-1 The System for C-V Measurement



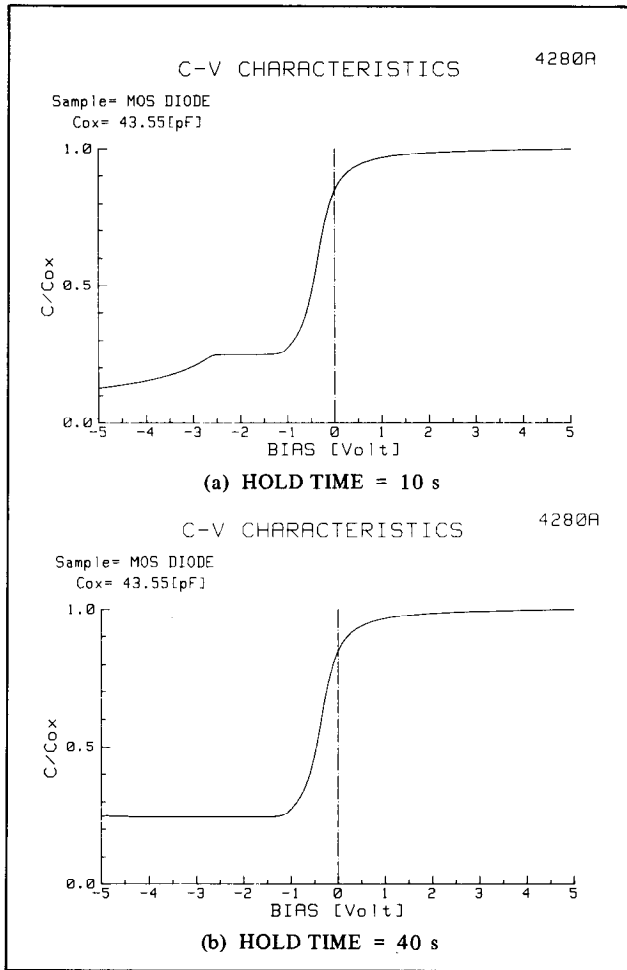


Figure 2-2 C-V Characteristics of MOS Diode

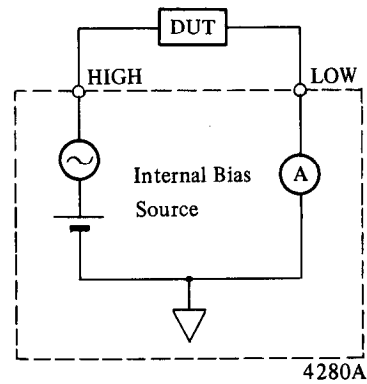


Figure 2-3 Connection (CN10)

## 2.2 How to Calculate Semiconductor Parameters

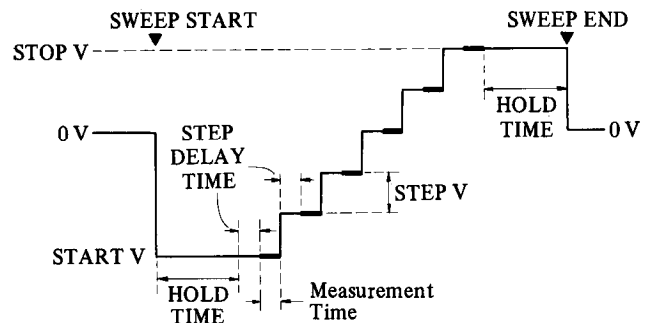
To calculate semiconductor parameters from C-V characteristics, the  $C_{ox}$  (oxide layer capacitance) must be measured and the  $N_{sub}$  (impurity concentration of substrate) obtained from the depletion layer capacitance must be computed. The reliability of parameters largely depends on the accuracy and resolution of measured  $C_{ox}$  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 equilibrium 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 $\pm 100$ 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.

$$N_{sub} = \frac{4 \cdot |\phi_f|}{q \cdot \epsilon_0 \cdot \epsilon_{si}} \cdot \left( \frac{C_{smin}}{A} \right)^2$$

$$\phi_f = \pm \frac{k \cdot T}{q} \ln \left( \frac{N_{sub}}{n_i} \right) \begin{pmatrix} + : \text{p-type} \\ - : \text{n-type} \end{pmatrix}$$

where

- $\phi_f$  is the Fermi potential, in Volts;
- $C_{smin}$  is the minimum depletion layer capacitance, in Farads;
- $A$  is the area of the gate (A1), in  $\text{cm}^2$ ;
- $n_i$  is the intrinsic carrier concentration per  $\text{cm}^3$ ;
- $\epsilon_0$  is the free space permittivity ( $8.854 \times 10^{-14} \text{ F/cm}$ );
- $\epsilon_{si}$  is the dielectric constant of Si (11.7);
- $q$  is the magnitude of electronic charge ( $1.602 \times 10^{-19} \text{ Coulomb}$ );
- $k$  is the Boltzmann constant ( $1.38 \times 10^{-23} \text{ J/K}$ ); and
- $T$  is the absolute temperature, in K.

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

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

where

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

(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:

$$C_{fb} = \frac{C_{ox} \cdot C_{sfb}}{C_{ox} + C_{sfb}}$$

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

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

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

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

$$\begin{aligned} C_{sfb} &= 9.615 \times 10^{-11} [\text{F}] \\ C_{fb} &= 2.997 \times 10^{-11} [\text{F}] \end{aligned}$$

Therefore Vfb is equal to  $-0.25 \text{ V}$ .

(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:

$$\frac{Q_{ss}}{q} = \frac{C_{ox}}{A \cdot q} |\Phi_{MS} - V_{fb}|$$

where  $\Phi_{MS}$  is the difference in the work functions of semiconductor (Si) and metal (Al). In this MOS diode, the following hold.

$$\begin{aligned} \phi_f &= -0.3061 \text{ V} \\ \Phi_{MS} &= -0.6 - \phi_f = -0.2939 \text{ V} \end{aligned}$$

Therefore,

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

(4) **Vth: threshold voltage**

Vth is an important parameter in the analysis of MOSFET's Vth is defined by the following equation:

$$V_{th} = V_{fb} + \left( 2\phi_f - \frac{A \cdot Q_b}{C_{ox}} \right)$$

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

$$Q_b = \pm q \cdot N_{sub} \cdot \frac{\epsilon_i \cdot \epsilon_{si} \cdot A}{C_{smin}} \begin{pmatrix} + : \text{n-type} \\ - : \text{p-type} \end{pmatrix}$$

In this MOS diode,

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

Therefore

$$V_{th} = -1.250 \text{ V}$$

### 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  $\tau_{\text{eff}}$  and  $S_0$  from these characteristics.

$\tau_{\text{eff}}$  (minority carrier lifetime in semiconductor bulk) and  $S_0$  (surface generation velocity) are very important parameters for evaluating the loss that occurs in charge-coupled devices (CCD) during charge transmission.

Measurement of  $\tau_{\text{eff}}$  and  $S_0$  is essential for the evaluation of Si wafers and for the study of new devices. Since  $\tau_{\text{eff}}$  and  $S_0$  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 ( $t_d$ ) can be set from 10 ms to 32 s. To set up the C-t measurement, set the parameters Pulse V, Meas V,  $t_h$ ,  $t_d$ , 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  $t_h$ , then the bias changes to MEAS V. This changing point defines  $t = 0$ . Then measurements are made at intervals of  $t_d$  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.).

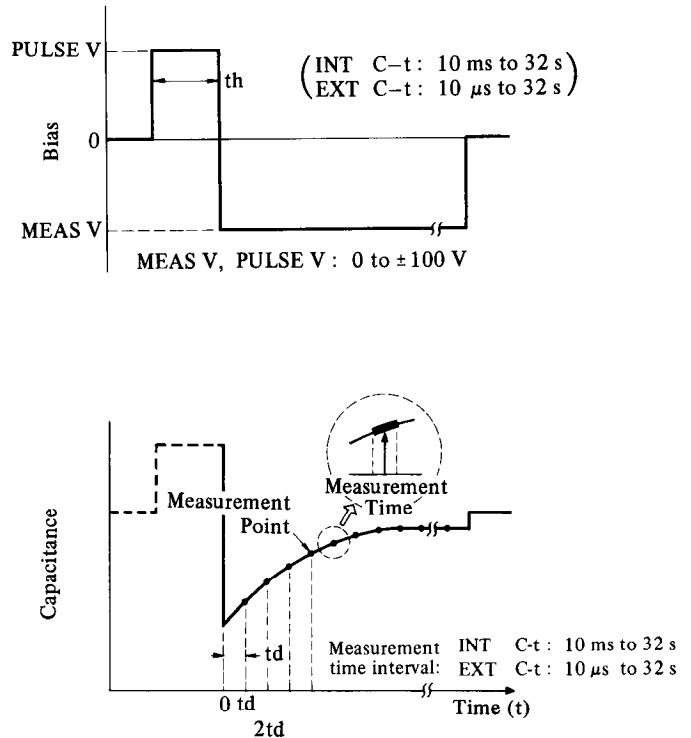


Figure 3-1 C-t Measurement

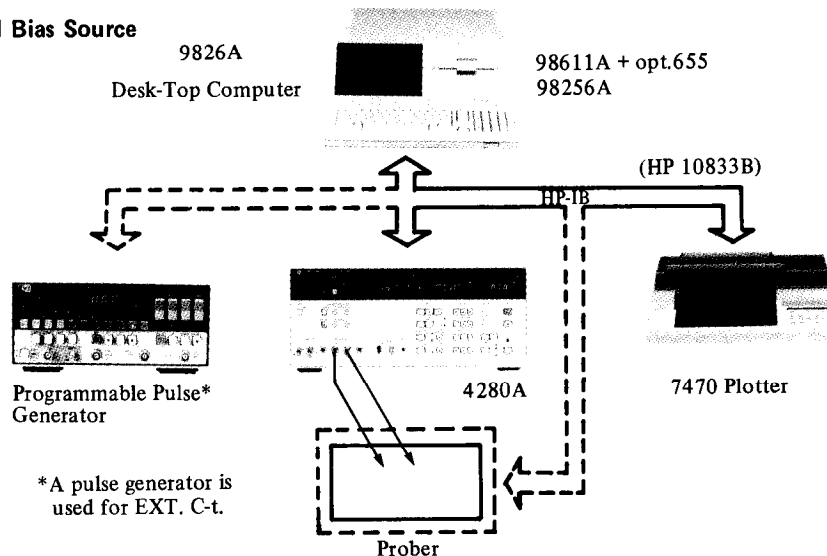


Figure 3-2 Example System for C-t Measurement and Zerbst Analysis

**< Example of Measurement >**

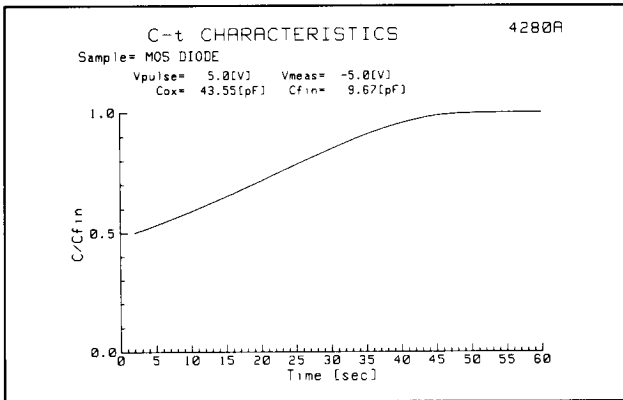
Figure 3-3 shows C-t characteristics for an n-type MOS diode measured under the following conditions:

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

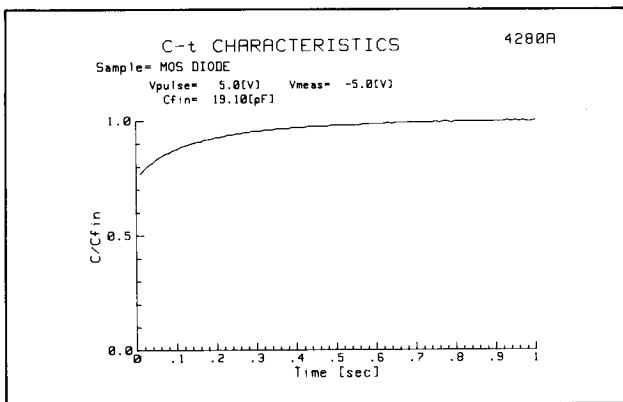
The MOS diode is forced into accumulation by applying a 5 V bias for 5 s then the bias is changed to -5 V. 60 measurements are then made at intervals of 1 s.

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  $td \geq 10 \mu s$  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:  $td \geq 200 \mu s$   
 EXT FAST:  $td \geq 10 \mu s$

**< Example of Measurement >**

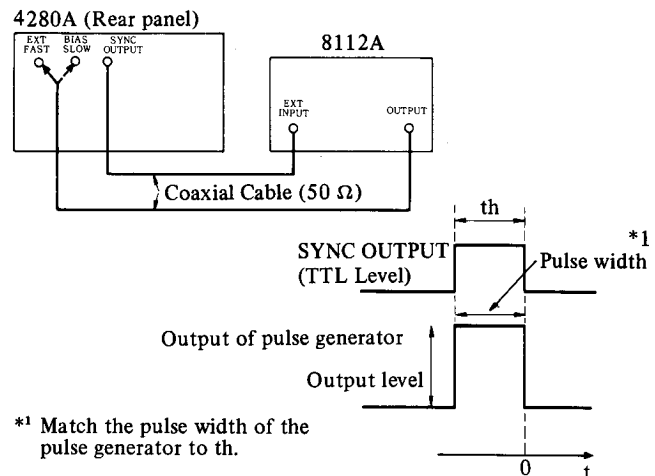
In this example, an HP 8112A Programmable Pulse Generator is used as an external pulse bias source for measuring the C-t characteristics of a MOS diode. Set the 4280A and 8112A as follows:

- 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  $\mu s$

- 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**

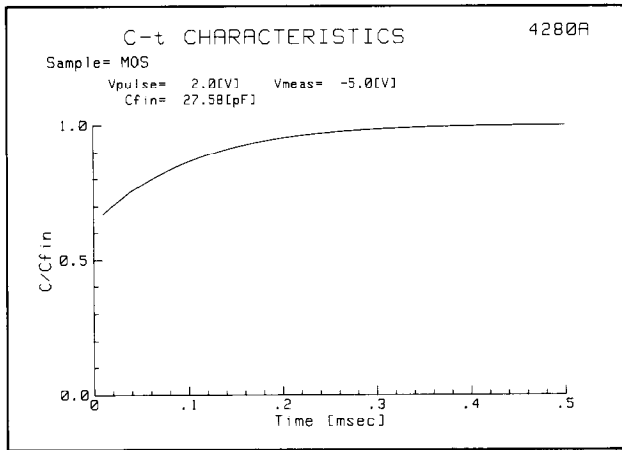


Figure 3-6 Measurement Results for a MOS Diode in the EXT C-t Mode ( $t_d = 10 \mu s$ )

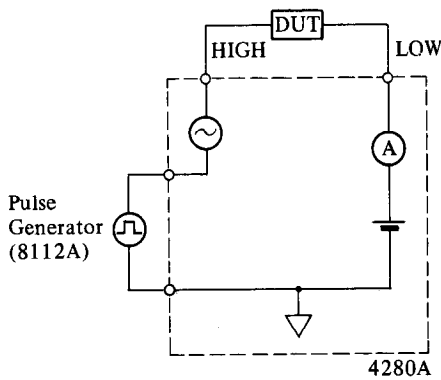


Figure 3-7 Connection Mode (CN13)

### 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,  $\tau_{\text{eff}}$ , and the surface generation velocity,  $S_0$  are calculated from Zerbst characteristics.

Zerbst characteristics can be obtained by plotting the following data.

$$\frac{C_{\text{fin}}}{C} - 1 \quad \text{VS} \quad -\frac{d}{dt} \left( \frac{C_{\text{ox}}}{C} \right)^2$$

(X axis)  (Y axis)

where

- C is the measured capacitance, in Farads;
- $C_{\text{fin}}$  is the final (equilibrium) capacitance, in Farads;
- $C_{\text{ox}}$  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 ( $\Delta$ ).  $\tau_{\text{eff}}$  and  $S_0$  are obtained from the following equations:

$$\tau_{\text{eff}} = 2 \cdot \frac{n_i}{N_{\text{sub}}} \cdot \frac{C_{\text{ox}}}{C_{\text{fin}}} \cdot \frac{1}{m} \quad [s]$$

$$S_0 = \frac{1}{2} \cdot \frac{N_{\text{sub}}}{n_i} \cdot \frac{\epsilon_{\text{si}} \cdot \epsilon_0 \cdot A}{C_{\text{ox}}} \cdot \Delta \quad [\text{cm/s}]$$

### Sampling Mode Measurement

High-resolution C-t measurement can be made in the sampling mode even when the measurement time interval ( $t_d$ ) is as short as  $10 \mu s$ .

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

For example, when the measurement speed is FAST and  $t_d$  is  $10 \mu s$ , at  $k = 1$  ( $t = 10 \mu s$ ),

$$t_s = 2 \mu s$$

$$\text{Number of samples} = 500$$

at  $k = 20$  ( $t = 200 \mu s$ ) then,

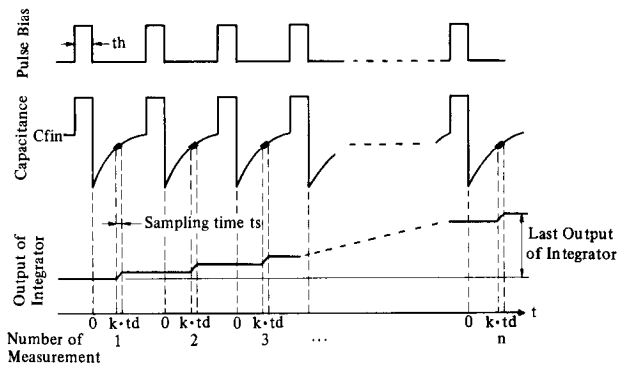
$$t_s = 40 \mu s$$

$$\text{Number of samples} = 25$$

The number of samples decreases as  $t (= k \cdot t_d)$  increases because the sampling time ( $t_s$ ) can be set larger as  $t$  increases. The number of samples is set automatically to the

most suitable value for each measurement,  $t (= k \cdot t_d)$ . 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  $t = k \cdot t_d$ )

where

- $n_i$  is the intrinsic carrier concentration, per  $\text{cm}^3$ ;
- $N_{\text{sub}}$  is the impurity concentration in the substrate,
- $\epsilon_{\text{si}}$  is the dielectric constant of Si (equals 11.7);
- $\epsilon_0$  is the permittivity of free space, ( $8.854 \times 10^{-14} \text{ F/cm}$ ) and
- $A$  is the area of the gate, in  $\text{cm}^2$ .

From Figure 3-8 we obtain

- $m \approx 2.999, \Delta \approx 0.2956$
- $C_{\text{ox}} = 43.55 \text{ pF}, C_{\text{fin}} = 9.67 \text{ pF},$
- $N_{\text{sub}} = 1.406 \times 10^{15} \text{ cm}^3$  (See page 8.)

And also

- $\tau_{\text{geff}} = 1.625 \times 10^{-5} \text{ s}$
- $S_0 = 6.498 \times 10^{-1} \text{ cm/s}$
- ( $T = 293 \text{ K}, A = 0.001 \text{ cm}^2$ )

A computer can be used with the HP 4280A to obtain  $\tau_{\text{geff}}$  and  $S_0$  more easily.

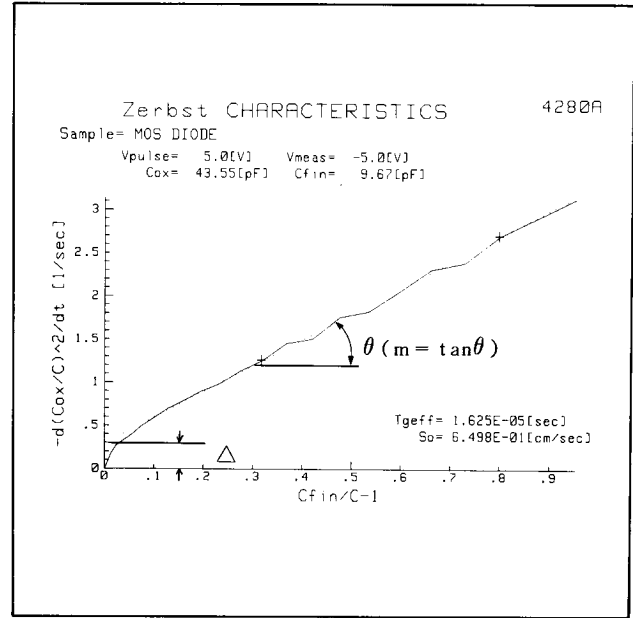


Figure 3-8 Zerbst Characteristics

## 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:

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

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

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  $-100 \text{ V}$  to  $+100 \text{ V}$ , 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  $\mu\text{r}$  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  $(0.05 \cdot \Delta V + 1.7) \text{ ms}$  (e.g.  $-5 \text{ V} \rightarrow 5 \text{ V}$  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)  $t_h$  is the accumulation time (see Figure 4-1.)
- ii)  $t_d$  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  $10 \mu\text{s}$  and  $2 \mu\text{s}$ . (See page 11 for the EXT FAST C-t mode and  $t_d = 10 \mu\text{s}$ .) 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  $\mu$ s
- 8112A  
 Mode: External width  
 Output Level:  $V_{acc}$ ,  $V_{inv}$ , and Bias step are set by HP-IB control (Figure 4-1 shows the  $V_{acc}$ ,  $V_{inv}$ , and bias step.)

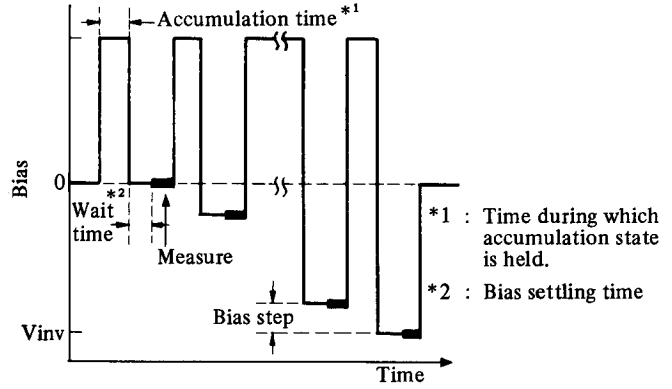


Figure 4-1 Pulsed C-V Measurement

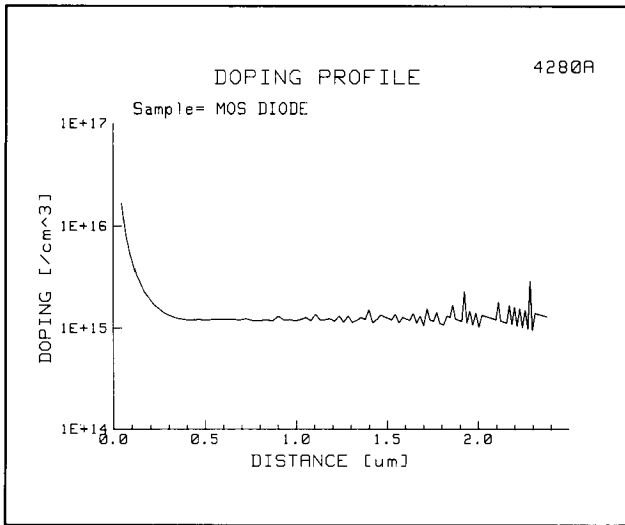


Figure 4-2 Doping Profile

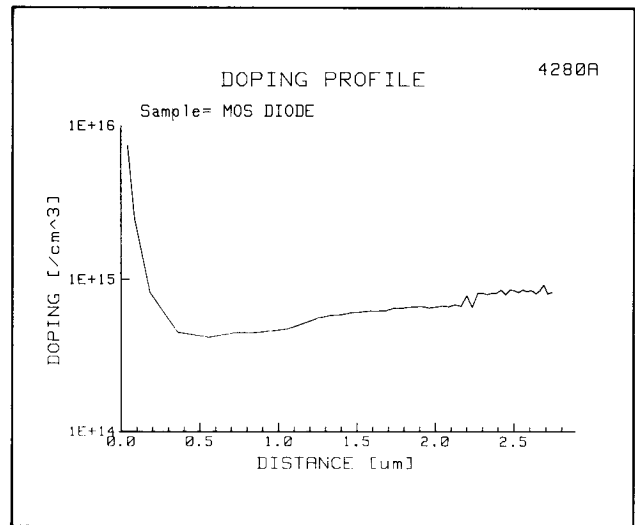


Figure 4-3 Doping Profile (EXT C-t Mode)

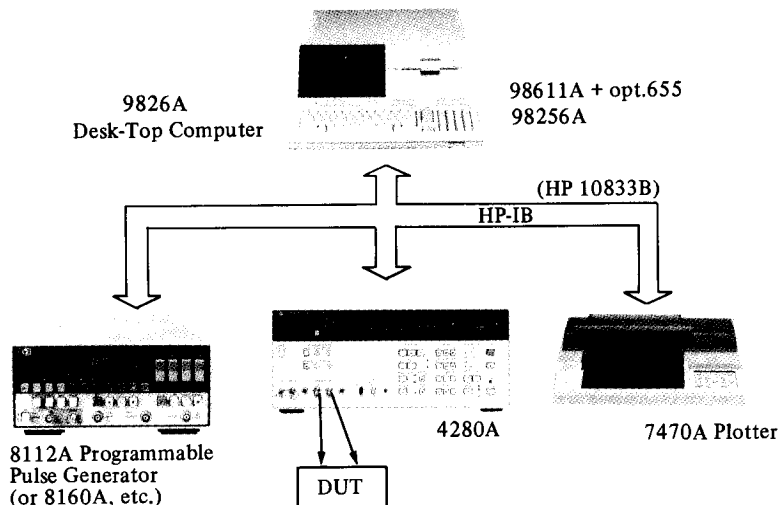


Figure 4-4 Example System for Doping Profile Measurement in the EXT C-t Mode

# <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.

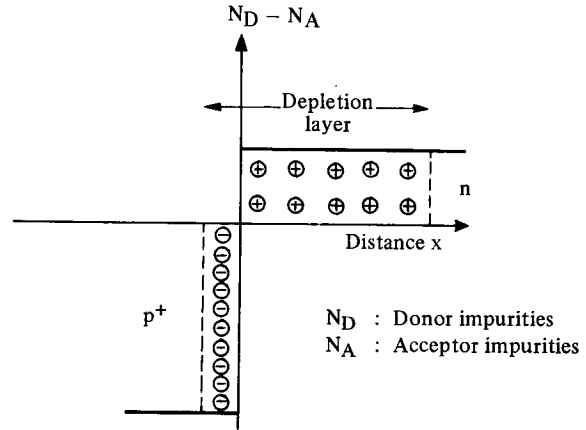


Figure I-1 The Abrupt pn Junction

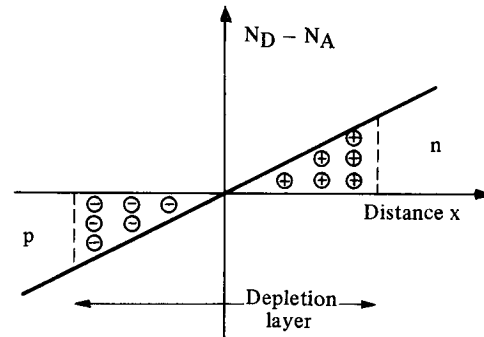


Figure I-2 The Linearly Graded pn Junction

		Abrupt pn Junction (one-sided)	Linearly Graded pn Junction
Theoretical Equation for C-V characteristics		$C = \sqrt{\frac{q \cdot \epsilon_s \cdot N_{sub}}{2(V_{bi} + V)}} \text{ per unit area}$ <p>or</p> $\frac{1}{C^2} = \frac{2}{q \cdot \epsilon_s \cdot N_{sub}} (V_{bi} + V)$ <p>where</p> <p>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<sup>3</sup> (If <math>N_A \gg N_D</math>, then <math>N_{sub} = N_D</math>);  Vbi is the built-in in potential, in Volts;  a is the impurity gradient, per cm<sup>4</sup>;  <math>\epsilon_s</math> is the semiconductor permittivity, in Frads per cm; and  q is the magnitude of electronic charge, in Coulombs.</p>	$C = \left[ \frac{q \cdot a \cdot \epsilon_s^2}{12(V_{bi} + V)} \right]^{1/3} \text{ per unit area}$ <p>or</p> $\frac{1}{C^3} = \frac{12}{q \cdot a \cdot \epsilon_s^2} (V_{bi} + V)$
Parameters obtained from C-V Characteristics	Vbi Nsub or a	<p>By graphing V (x-axis) vs <math>1/C^2</math> (y-axis)</p> $N_{sub} = \frac{2}{q \cdot \epsilon_s \cdot m} [1/\text{cm}^3]$ $V_{bi} = \frac{\Delta}{m} [V]$ <p>where</p> <p>m is the slope, and <math>\Delta</math> is the intercept of y-axis.</p>	<p>By graphing V (x-axis) vs <math>1/C^3</math> (y-axis)</p> $a = \frac{12}{q \cdot \epsilon_s^2 \cdot m} [1/\text{cm}^4]$ $V_{bi} = \frac{\Delta}{m} [V]$ <p>where</p> <p>m is the slope, and <math>\Delta</math> is the intercept of y-axis.</p>
	Doping Profile	$N(W) = \frac{2}{q \cdot \epsilon_s \cdot A^2} \left[ \frac{d}{dv} \left( \frac{1}{C^2} \right) \right]^{-1} [1/\text{cm}^3]$ $W = \frac{A \cdot \epsilon_s}{C} [\text{cm}]$ <p>where A is the area of the gate in cm<sup>2</sup>.</p>	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,  $t_d \geq 200 \mu s$ ) 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  $t_d$  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  $t_d$  as short as  $10 \mu s$  to be performed.

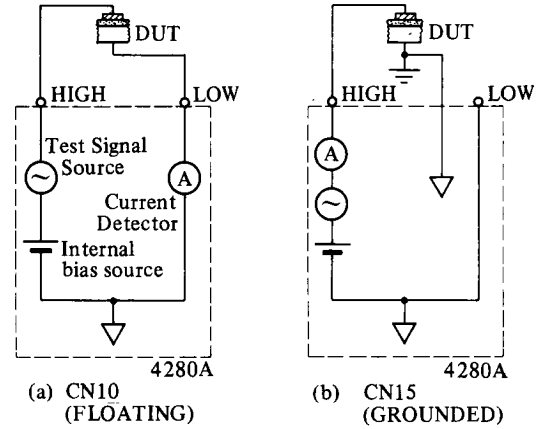


Figure II-1 Connection for Measurements on Floating and Grounded DUTs

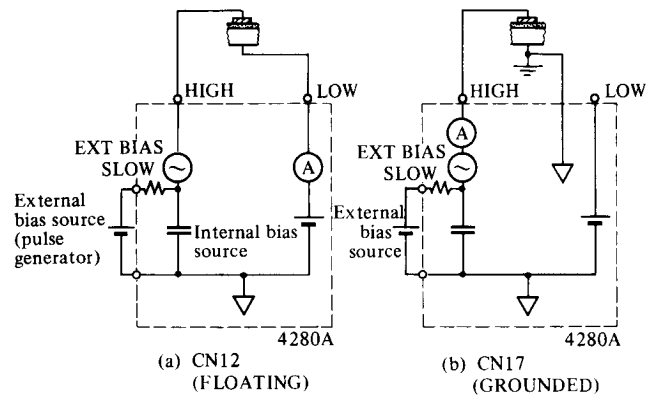


Figure II-2 Connection for EXT SLOW C-t Measurement ( $t_d \geq 200 \mu s$ )

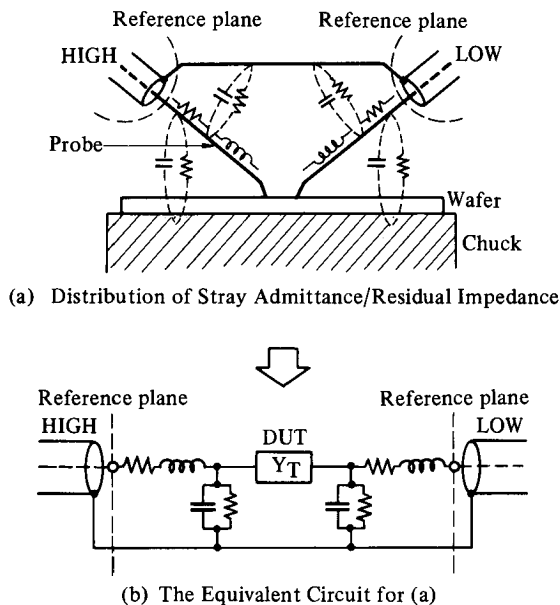


Figure II-3 Errors in a Measurement System

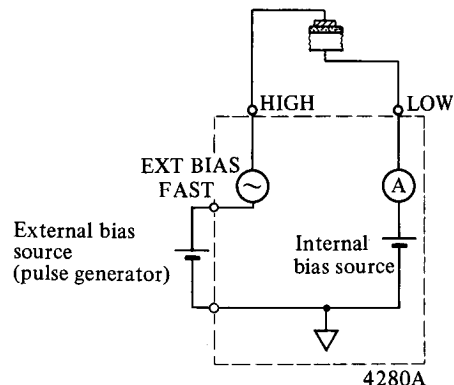


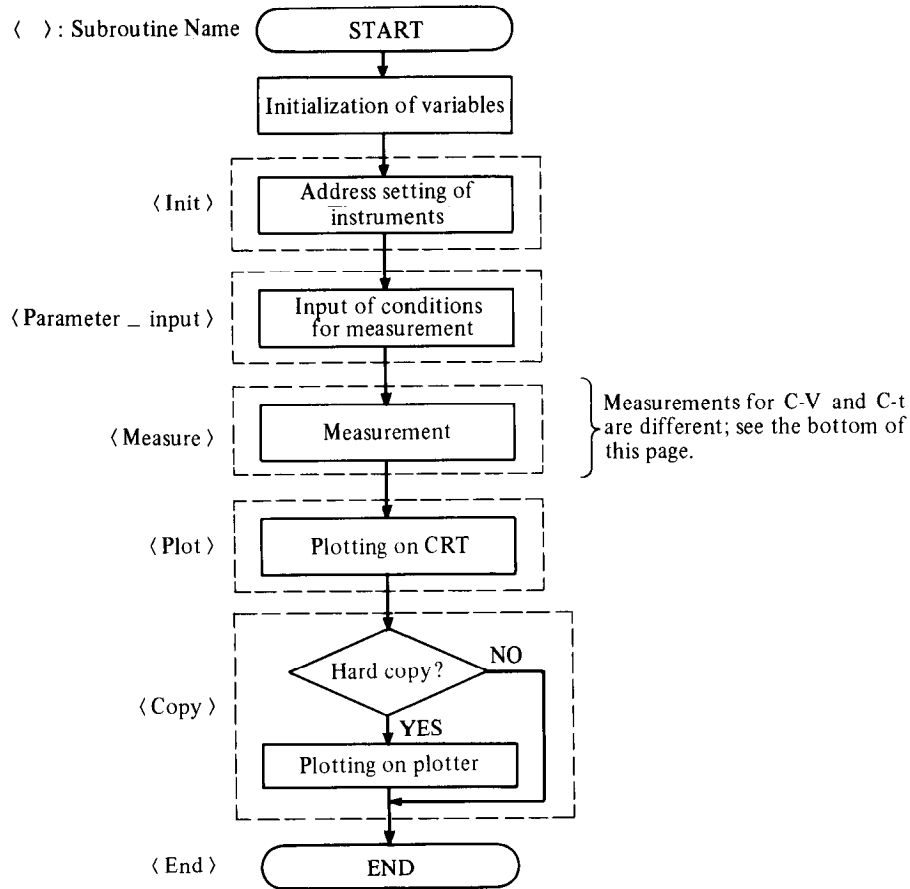
Figure II-4 Connection for EXT FAST C-t Measurement (CN13)

### 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).



(1) < Measure > of C-V Measurement

(2) < Measure > of C-t Measurement

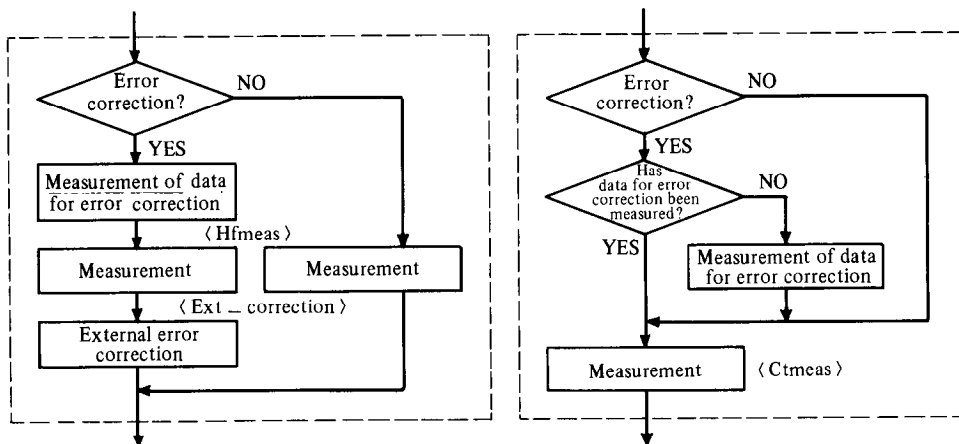


Figure III-1 Flow Chart of C-V/C-t Programs

## (1) C-V Measurement Program

```
10 ! C-V MEASUREMENT at 1MHz
20 ! BINARY FORMAT TRANSMISSION
30 OPTION BASE 1
40 DIM Bias(501),Va11(501),Va12(501),Va13(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,MDO,MA0,DC0,DGO,FL,AS,BC,ISO,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_1,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_1,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,1,2,2,10)
1210 !
1220 OUTPUT Cmeter80;"CEO,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 Cddd=C*C+D*D
2350 Ytx=(A*C+B*D)/Cddd
2360 Yty=(B*C-A*D)/Cddd
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,Dev)
3970 OUTPUT Cmeter80 USING 3980;Dev
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,BLO,M00,MA0,DC0,DG0,FL,AS,BC,ISO,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,NO=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,S,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,S,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;"BLO"
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;"BLO,MDO"
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.D," [pF]";X," Cfin= ",3D.D," [pF]"
2680 RETURN
2690 !
2700 ! ***** SUB(End) *****
2710 End: !
2720 DISP "          END          "
2730 PAUSE
2740 END
2750 !
2760 ! -----
2770 ! ----- SUB PROGRAM -----
2780 ! -----
2790 ! *** SUB(Para80) *****
2800 !
2810 SUB Para80(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_l,Ibias,Conn)
2920 OUTPUT Cmeter80 USING 2930;Cable,R_m,R_a,Func,M_s,S_l,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;Ra
3220 P=SPOLL(Cmeter80)
3230 IF BIT(Ra,0)=0 THEN GOTO Not_data_ready
3240 Data_ready=1
3250 WAIT .1
3260 Not_data_ready: !
3270 SUBEND

```

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