A Low Cost C-V Meter for Characterizing Semiconductor Devices

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Abstract
A simple and low cost quasi-static capacitance-voltage (C-V) meter was designed and developed to obtain C-V characteristics of semiconductor devices based on a C8051F006 SoC (system on-a-chip). The developed C-V meter consists of a capacitance meter based on feedback charge amplifier, a programmable voltage source, a C8051F006 SoC-based slave controller, and a personal computer (PC) as a master controller. The accuracy of the C-V meter is guaranteed by the calibration functions, which are employed by the program in the PC and it is obtained through the calibration processes of analog to digital converter (ADC), digital to analog converters (DACs) of the C8051F006 SoC, and the programmable voltage source. Examining 33-pF and 1000-pF capacitors as well three different p-n junction diodes, it was found that the capacitances of common capacitors are in the range of specified values and typical C-V curves of p-n junction diodes are achieved.

Keywords: capacitance meter, C-V, feedback charge amplifier

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1. Introduction
Capacitances of semiconductor devices are relatively easy to measured, and are usually associated with relevant physical parameters. From determining the capacitances, a number of characterization techniques have been developed to assess the geometry of devices, component materials and interfaces. Various methods called as capacitive measurements are available and frequently in the form of C-V characteristics, such as; phase-sensitive detection, time-encoded ballistic, resonance, and AC bridge methods [1-6].

C-V curves are generally obtained by using an AC measurement technique. The semiconductor devices are usually biased at increasing voltages in a step sequence and superimposing a small ac voltage with the frequency in the range of 1 kHz to 10 MHz [6]. The AC measurement technique is also termed as high-frequency (HF) C-V measurement. On the other hand, there is a DC measurement technique, which is required by some capacitive measurement applications. This technique is called quasi-static C-V or low frequency (LF) C-V measurements because it performed at a very low frequency, at almost DC. These measurements usually involve stepping DC voltage and resulting current or charge [6].

Compared to the HF C-V measurements, intrinsic advantages of the quasi-static C-V are lie in convenience of the data acquisition and the simplicity of circuits [7]. Although the circuits are simple, there are only few papers describing the development of the quasi-static C-V meters [8-10]. Unfortunately, microcontrollers are not employed to control the quasi-static C-V meters.

In this paper, the development of a quasi-static C-V meter based on the Silicon Laboratories C8051F006 SoC is reported. After calibrating the developed C-V meter, the C-V meter is employed to characterize the semiconductor devices such as capacitors and diodes. The C–V curves obtained by the C-V meter are analyzed and discussed.
2. Design and Method

Figure 1 demonstrates a block diagram of the quasi-static C-V meter. It is composed of a capacitance meter, a programmable voltage source that generates DC bias voltage and voltage step, a C8051F006 SoC which acts as a slave controller, and a PC functions as a master controller. The communication between the master and slave controllers is provided by RS 232 serial communication. The output of voltage source is fed to the device under test (DUT) and its capacitance is measured by the capacitance meter.

As explicitly shown by its name, the C8051F006 SoC provides enormous features [11]. The important subsystems utilized by the quasi-static C-V meter are two 12-bit DACs, i.e. DAC0 and DAC1, a 12-bit ADC and an 8051 microcontroller. As a slave controller, the C8051F006 SoC controls directly and communicates to the capacitance meter and the voltage source. Through the slave controller, pairs of applied voltages and measured capacitances are saved in the PC for further processing.

The capacitance meter uses a feedback charge method and utilizes the quasi static measurement method to measure the capacitance. The advantages of employing the feedback charge method are higher signal to noise ratio at frequencies of interest, independence of signal size from measurement time, and the ease of distinction of signal charge from error currents at the time of measurement [12]. Since the DC bias voltage which is supplied to the DUT can be in negative, it is contrast to the input voltage of the ADC of the C8051F006 SoC, where an absolute amplifier is required. The quasi static measurement method applies a small voltage step across the DUT and a displacement charge where it is stimulated and measured.

The voltage source supplies a DC voltage to fulfill the requirements of the quasi static measurement method. The DC bias voltage can be positive or negative respectively. The DC bias voltages are generated by the ones outputs of DACs of the C8051F006 SoC. The positive bias is directly delivered by DAC0. As the output of the DAC is positive, the negative bias is achieved by employing DAC1 and an inverter amplifier. A small voltage step ranging from 100 mV to 3.2 V is produced by resistor ladders together with a precision voltage supply, a 4051 multiplexer, and a buffer amplifier. The selection of voltage step is performed by the C8051 microcontroller of the C8051F006 SoC. Making use of a summing amplifier, the output of the voltage source is a small voltage step \( V_{step} \) superimposing a DC bias voltage respectively.

A circuit diagram of the feedback charge method is shown in Figure 2. It is an integrator circuit with a feedback capacitor \( C_f \), a switch \( S \), and a capacitance to be measured \( C_x \). Before performing a measurement, the feedback capacitor is discharged by closing the switch. For the
measurement the switch is opened to charge the $C_r$. As a result, there is a charge $\Delta Q$, which is supplied by the bias voltage and transferred to $C_r$ of the integrator. This charge results in a change of the integrator output, which is given by:

$$\Delta V_{\text{out}} = -\frac{\Delta Q}{C_r} \quad (1)$$

Figure 2. Feedback charge circuit

Applying the quasi static measurement method, the voltage source is changed by a small amount $dV$ of a voltage step. This voltage step produces a displacement charge, $dQ$ to be transferred to the DUT of $C_r$. The displacement charge in $C_r$ is proportional to the voltage change and is given as $dQ = C_r dV$. The charge in the $C_r$ is determined by measuring the integrator output before and after the application of the voltage step and is written as:

$$\Delta dQ = -C_r \Delta V_{\text{out}} \quad (2)$$

The $C_r$ of the DUT is therefore given as
\[ C_x = \frac{\Delta Q}{\Delta V} = -C_x \frac{\Delta V_{\text{out}}}{\Delta V} \] (3)

The way of measuring the \( C_x \) of the DUT is described as follows. The voltage waveform is fed to the DUT by the voltage source at a bias voltage is shown in Figure 3(a). A DC bias voltage, \( V_{\text{bias}} \), is applied during the time of \( t_{\text{step}} \). A voltage step, \( V_{\text{step}} \), is then given during the next of \( t_{\text{step}} \). The charge waveform is given in Figure 3(b). The charge measurements are made at three specific times, which are represented by \( Q_1 \), \( Q_2 \), and \( Q_3 \). The \( Q_1 \) is the baseline charge, which is measured prior to the voltage step by \( t_1 \). The \( Q_2 \) is measured after specified delay time, \( t_{\text{delay}} \), where \( t_{\text{step}} = t_{\text{delay}} + t_1 \), it is an indication of the final charge transferred to \( C_x \). The \( Q_2 \) is measured before \( Q_3 \) by \( t_0 \). The \( Q_3 \) is used to determine the slope of charge waveform. This slope indicates the amount of current, \( Q/t \), flowing in the \( C_x \) during the final portion of \( t_0 \). The \( Q/t \) represents the leakage in the \( C_x \) and corrected capacitance is calculated as follows:

\[ C_{\text{corr}} = C_x \frac{(Q_2/Q_1) + (t_{\text{delay}} + t_1)}{V_{\text{step}}} \] (4)

A flowchart of measuring capacitance is described in Figure 4. The PC feeds a bias voltage, a voltage step, and a time delay to the microcontroller of the C8051F006 SoC. Before doing measurement, the \( C_f \) is discharged. As the measurement is carried out \( V_{\text{bias}} \) is applied to the \( C_x \) for a given delay time. The output voltage of capacitance meter is read by the ADC and sent to the PC via the RS-232 serial communication.

3. Results and Discussion

In order to ensure the accuracy of the measurements, the developed C-V meter is calibrated as illustrated in Figure 5. The calibration of the ADC of C8051F006 SoC is first done as given in Figure 5(a). A precision voltage source supplied a voltage, which is also measured by the Fluke 45 voltmeter, to the ADC by connecting the C8051F006 SoC to the PC by the RS 232 serial communication, the output of ADC is saved into the PC. The voltages measured by the voltmeter are compared to obtain a calibration function for the ADC. Figure 5(b) shows the calibration of DACs with the voltage source. The PC sent a digital data, which represent certain voltages to the DAC and the Fluke 45 voltmeter measured the output of the voltage source. The voltages provided by the PC are compared those measured by the voltmeter to get a calibration function for the DAC and the voltage source.

Figure 6 shows a transfer function of an input and an output of the ADC. Here, the 12-bit digital output of the ADC is given as decimal numbers. It is shown that the straight line is represented by \( y(x) = (5.98 \times 10^4) x \), where \( y \) is the input voltage and \( x \) is the digital output voltage. The equation is a calibration function of the ADC and it will be used by the program in the PC.

Transfer functions of the DACs with the voltage source are shown in Figure 7. The 12-bit digital input of the DAC is presented as decimal numbers. Symbols are measured values and the straight lines are fitting functions to the data. The straight lines act as calibration functions of the DACs with the voltage source that will be employed by the program in the PC. In addition, it is found that the calibration functions are \( y(x) = -668.8x - 3.7 \) and \( y(x) = 666.7x + 7.8 \) for negative and positive outputs where \( y \) is the digital input voltage and \( x \) is the output voltage.

The developed quasi-static C-V meter is examined to obtain C-V characteristics of semiconductor devices. The devices are 33-pF and 1000-pF capacitors as well as three different diodes. Applying the voltage step of 20 mV and the delay time of 500 ms to 33- and 1000-pF capacitors, the C-V curves are found as given in Figures 8(a) and 8(b). Since these are common capacitors, their capacitances are independent with bias voltages. The measured results confirmed the characteristics of the capacitors. The obtained variations are related to the precision of the repeated measurements. However, the measured values are within the range of specified capacitances.
Figure 5. Calibrations of (a) ADC and (b) DACs

Figure 6. A transfer function of the ADC

Figure 7. Transfer functions of the DACs with the voltage source; (a) Negative output and (b) Positive output

Figure 8. C-V characteristics of capacitors of (a) (33±5%) pF and (b) (1000±5%) pF
The C-V characteristic of 1N4002 general rectifier diode with reverse bias voltages is demonstrated in Figure 9(a). The curve is obtained by employing the voltage step of 10 mV and the time delay of 1000 ms. The datasheet gives the diode capacitance of 15 pF at a frequency of 1 MHz and a reverse voltage of 4 V [13]. On the other hand, the diode capacitance measured at very low frequency is about 600 pF. It seems that the diode capacitance depends on operating frequency and the increase in operating frequency would decrease the diode capacitance and plotting $1/C^2$ versus voltage. The graph is shown in Figure 9(b). The result implies that the diode has an abrupt junction [14].

$$y = 77.57x - 59.38 \quad R^2 = 0.939$$

Figure 9. 1N4002 rectifier diode in reverse bias with $V_{step} = 10$ mV and $t_{delay} = 1000$ ms. (a) C-V characteristic (b) $1/C^2$ vs V plot

A 1N4148 high-speed switching diode has a C-V characteristic under reverse bias voltages as depicted in Figure 10(a). A voltage step of 10 mV and the delay time of 1000 ms are used to achieve the curve. The datasheet which giving the diode capacitance of about 0.8 pF at a frequency of 1 MHz and a reverse voltage of 4 V [15], the diode capacitance obtained at very low frequency is about 500 pF. Again, it looks that the increase in operating frequency would decrease the diode capacitance. Figure 10(b) gives a plot of $1/C^2$ versus voltage as a straight line. It means that the diode has also an abrupt junction.

$$y = 7.603x + 0.441 \quad R^2 = 0.969$$

Figure 10. 1N4148 rectifier diode in reverse bias with $V_{step} = 10$ mV and $t_{delay} = 1000$ ms. (a) C-V characteristic. (b) $1/C^2$ vs V plot.
Figure 11(a) shows a C-V characteristic of an FR104 fast recovery diode under reverse bias voltages. The curve is obtained by employing a voltage step of 10 mV and the time delay of 400 ms. The datasheet provides the diode capacitance of 15 pF at a frequency of 1 MHz and a reverse voltage of 4 V [16]. On the contrary, it is found that the diode capacitance is obtained at very low frequency which about 600 pF. Once more, it appears that the increase in operating frequency would decrease the diode capacitance. A straight line of $1/C^2$ versus voltage in Figure 11(b) indicates that the diode has also an abrupt junction.

![Graph of FR104 diode C-V characteristic](image)

Figure 11. FR104 fast recovery diode in reverse bias with $V_{step}=10$ mV and $t_{delay}=400$ ms. (a) C-V characteristic. (b) $1/C^2$ vs V plot.

4. Conclusion

A simple and low cost of quasi-static C-V meter has been built based on a C8051F006 SoC to characterize semiconductor devices. The C-V meter is composed of a capacitance meter, a programmable dc voltage source, a C8051F006 SoC-based slave controller and a personal computer as a master controller. The C-V meter has been calibrated to obtain calibration functions, which are used by the program in the master controller. It has been shown that capacitances of 33-pF and 1000-pF capacitors are constant independent of bias voltages and the values are match with the indicated values. Moreover, typical C-V curves of p-n junction diodes have also obtained.

References

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