Charge-pumping measurements

A system that incorporates a pulse generator and a sensitive DC ammeter can reveal information about the quality of semiconductor devices.

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Charge pumping is a well-known technique for characterizing the semiconductor–dielectric interface of MOS structures. Labs can obtain invaluable information about the quality and degradation of a device from I_CP (charge-pumping-current) measurements, including information about the interface-trap density and the mean-capture cross section. To make I_CP measurements, you must pulse a gate voltage and measure a DC substrate current simultaneously, so you need a test system that incorporates both a pulse generator and a sensitive DC ammeter.

Figure 1 shows a charge-pumping measurement circuit. Essentially, the gate of a MOSFET connects to a pulse generator, which repeatedly switches the transistor from accumulation to inversion. While the gate is pulsed, a recombination process of minority and majority carriers occurs on the rising and falling edges of the pulses, causing a current to flow in the opposite direction of the normal drain-to-source current. You can measure this induced current, the I_CP, by connecting a sensitive ammeter to the substrate, or bulk terminal, of the MOSFET.

Although several charge-pumping methods have been developed, the basic technique involves measuring the substrate current while applying voltage pulses of fixed amplitude, rise time, and frequency to the transistor gate. The source and drain are either tied to ground or slightly reverse-biased. In the two most commonly used methods, the measurement equipment must apply the voltage pulse either with a fixed amplitude while sweeping the base voltage or with a fixed base voltage while sweeping the voltage amplitude of the pulse.

In the first method, the fixed-amplitude/voltage-base-sweep method, the amplitude and period (width) of the pulse are kept constant while the base voltage is swept from inversion to accumulation. Figure 2 illustrates both this output waveform and the resulting curve of the I_CP as a function of the base voltage. From this data, you can use the following equation to calculate the interface-trap-charge density:

\[ N_{IT} = \frac{I_{CP}}{(qfA)} \]

where:
- \( N_{IT} \) = interface-trap-charge density in cm\(^{-2}\),
- \( I_{CP} \) = charge-pumping current in A,
- \( f \) = test frequency in Hz,
- \( q \) = electron charge (1.6022 × 10\(^{-19}\) C), and
- \( A \) = channel area in cm\(^2\).
The following equation enables the extraction of the interface-trap density as a function of band bending:

\[ D_{IT} = \frac{I_{CP}}{q f A \Delta E} \]

where 

- \( D_{IT} \) = interface-trap-charge density in \( \text{cm}^{-2}\text{eV}^{-1} \), and 
- \( \Delta E \) = the difference between the inversion Fermi level and the accumulation Fermi level (Ref. 1).

In the second common technique, the fixed-base/variable-amplitude-sweep method, the base voltage is kept constant in accumulation, and the variable voltage amplitude is pulsed into inversion. As the voltage amplitude (\( V_{AMP} \)) of the pulses increases, \( I_{CP} \) saturates and stays saturated (Figure 3).

In addition to these two methods, engineers may also employ other charge-pumping techniques. For example, they can use different voltage waveform shapes, vary the rise and fall times, or measure the charge-pumping current as a function of frequency.

**Hardware configuration**

The equipment used to make charge-pumping measurements has traditionally included a pulse generator and a DC ammeter capable of measuring current in the picoamp range. Figure 4 illustrates a more modern configuration that employs a semiconductor parameter analyzer with an integrated pulse generator and two SMUs (source-measure units), one of which is equipped with a preamplifier for measuring ultralow currents.

The pulser connects to the gate of the MOSFET in order to apply pulses of sufficient amplitude to drive the device between inversion and accumulation. Depending on the charge-pumping method used, the pulser allows users to sweep the pulse amplitude, sweep the base voltage, adjust the rise and fall times, and vary the test frequency. The test frequency is usually in the kilohertz to megahertz range.

As shown in Figure 4, SMU1 connects to the bulk terminal and measures the resulting substrate current. Given that \( I_{CP} \) is often in the nanoamp or picoamp range, an SMU equipped with a preamp is typically required to achieve the necessary sensitivity.

The source and drain terminals of the MOSFET are tied together and connected to the second SMU (SMU2), which applies a slight reverse bias (\( V_{R} \)). If \( V_{R} = 0 \), then the source and drain terminals can be connected to the ground unit rather than to SMU2.

To prevent oscillations and minimize noise, it is important to connect the LO (common) terminals of all the SMUs and the pulser as close as possible to the DUT (device under test). To minimize noise caused by electrostatic interference in low-current measurements,

**FIGURE 3.** The pulse waveform for a fixed-base/variable-amplitude sweep (top) results in the corresponding charge-pumping current curve (bottom).

**FIGURE 4.** In this configuration for charge-pumping current measurements, a pulser applies pulses to the gate of a transistor under test. The SMU2 voltage source supplies a reverse bias to the source and drain (which alternatively can be tied to common), while SMU1, which includes a preamplifier, measures \( I_{CP} \).

**FIGURE 5.** These curves show the results of measuring charge-pumping current as a function of the base voltage (a) or as a function of pulse amplitude (b).
engineers must shield the DUT by placing it in a metal enclosure with the shield connected to the LO terminal of the SMU.

**Charge-pumping-test variations**

You can add software libraries to the setup shown in Figure 4 to automate both the fixed-amplitude/voltage-base-sweep and the fixed-base/variable-amplitude-sweep charge-pumping tests (Ref. 2). You can also use this setup to perform several variations on those basic methods; in all of the methods, except where modifications are noted, the source and drain terminals are tied to ground:

- In the base-sweep technique, the tester sweeps the base voltage of the waveform while keeping the amplitude of the pulse constant (Figure 2). It graphs $I_{CP}$ as a function of the base voltage (Figure 5a). A modification to this technique adds a second SMU to apply a DC voltage bias to the source and drain terminals.

- In the amplitude-sweep technique, the tester sweeps the amplitude of the pulse while keeping the base voltage constant (Figure 3). It graphs $I_{CP}$ as a function of the pulse-amplitude voltage (Figure 5b). As with the base-sweep technique, you can modify this technique by adding a second SMU to apply a DC voltage bias to the source and drain terminals.

- In the rise-time linear-sweep technique, the tester performs a linear sweep of the rising transition time of the pulse, and it graphs $I_{CP}$ as a function of the rise time.

- In the fall-time linear-sweep technique, the tester performs a linear sweep of the falling transition time of the pulse and graphs $I_{CP}$ as a function of the fall time.

- In the frequency linear-sweep technique, the tester holds the amplitude, offset voltage, and rise and fall times constant and measures $I_{CP}$ as a function of a linear sweep of the test frequency. In the frequency log-sweep variation, the tester graphs $I_{CP}$ as a function of a log sweep of the test frequency.

**REFERENCES**


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