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MOS-C-V TECHNIQUE TO DETERMINE IMPURITY
CONCENTRATIONS AND SURFACE PARAMETERS ON THE
DIFFUSED FACE OF SILICON SOLAR CELLS (NASA)
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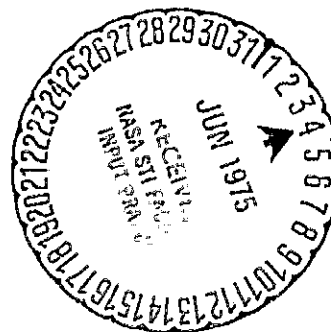
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APPLICATION OF THE MOS C-V TECHNIQUE TO DETERMINE
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ABSTRACT

The MOS C-V technique has been widely used, with SiO₂ as the oxide, to determine surface state parameters on silicon with carrier concentrations less than 10¹⁸ cm⁻³. However, at higher impurity concentrations, especially those encountered on the n⁺ solar cell surface (N ≈ 10²⁰ cm⁻³), the MOS technique using SiO₂ is relatively insensitive. Increased sensitivity is expected for oxides with higher dielectric permittivity. In this respect, Ta₂O₅ with a dielectric permittivity considerably larger than SiO₂ affords a distinct advantage. It is also in use as the antireflection coating on improved solar cells. Hence, an experimental and theoretical investigation has been conducted into the feasibility of using the MOS C-V technique to obtain information regarding impurity and surface state concentrations on the diffused face of silicon solar cells with Ta₂O₅ coatings.

The current data yield the result that the impurity concentration, approximately 10 Å from the diffused surface, has the value 2.9x10²⁰ cm⁻³. In addition, it is found that N_s, the density of charge in surface and oxide states has the value 2.1x10¹³ cm⁻². The C-V data are found to be in reasonable agreement with theoretical predictions. Based on these results it is concluded that the MOS C-V technique yields useful information concerning surface parameters which contribute to the high, efficiency limiting, surface recombination velocities on the n⁺ surface of silicon solar cells.

INTRODUCTION

Increases in solar cell efficiency can be effected through a reduction in surface recombination velocity (1). However, a scarcity of information exists concerning the diffused face of the silicon solar cell. This lack of information arises from the difficulties which occur when attempting to obtain experimental data regarding the surface of heavily doped semiconductors. The MOS capacitance-voltage technique is commonly used for determining the number and nature of surface states on silicon (2, 3, 4). Most of the work in this area has been concerned with thermally oxidized SiO₂ on silicon and has been limited to silicon carrier concentrations below 10¹⁸ cm⁻³. This limitation arises from the fact that the sensitivity of the technique decreases with increasing carrier concentration. However, concentrations in the 10²⁰ cm⁻³ range (5) are the usual case for the diffused silicon solar cell face. Hence it becomes necessary to extend use of the technique outside the limits of current usage. This can be done if a method, independent of bulk semiconductor concentration variation, can be utilized to attain increased sensitivity. In this respect, it is known that sensitivity increases with increased dielectric permittivity of the oxide used in the MOS capacitor (2).

Silicon monoxide, a widely used antireflection coating on silicon solar cells, has a dielectric permittivity slightly higher than SiO₂. However, Ta₂O₅, a coating used on improved solar cells (6) has a dielectric permittivity considerably greater than either SiO or SiO₂. Hence use of Ta₂O₅ affords the advantage of increased sensitivity. Numerical calculations will be presented later in this paper to support this asser-

tion. For the present, it is noted that the properties of the oxide-semiconductor interface will vary, depending on the oxide used as the antireflection coating. Thus investigation of the diffused face on Ta₂O₅ coated solar cells has a high degree of relevancy since a practical antireflection coating is used. In addition, the technique is non-destructive and has the potential for use as an aid to quality control in solar cell production. The objective of the present work is thus to experimentally investigate the feasibility of using the MOS C-V technique to obtain information concerning the heavily doped, diffused face of silicon solar cells with Ta₂O₅ as the antireflection coating.

THEORETICAL RELATIONS

The purpose of this section is to introduce the mathematical formulae used in extracting surface parameters from the experimental data. Prior to this, however, a calculation is carried out to show the enhancement in sensitivity which results from increased oxide dielectric permittivity.

Sensitivity

The sensitivity of the MOS C-V technique varies inversely with C_{min}/C_{max} the ratio between minimum and maximum capacitance observed as the applied dc voltage is varied through the measurement range. At high frequencies, numerical estimates of this ratio can be obtained from the relation (2, 7).

$$\frac{C_{min}}{C_{max}} = \frac{1}{1 + \frac{2\epsilon_0}{qd} \left(\frac{kT \ln \frac{N}{n_i}}{\epsilon_s N} \right)^{1/2}} \quad (1)$$

where ϵ_0 is the oxide dielectric permittivity, d is oxide thickness, q is the electronic charge, k is Boltzmann's constant, T the temperature, N the donor concentration, n_i the intrinsic carrier concentration, and ϵ_s the dielectric permittivity of silicon. Equation (1) clearly illustrates that for given values of d , N , ϵ_s , and T , the sensitivity increases for increased values of ϵ_0 . The results for $N = 10^{20}$ cm⁻³ are shown in figure 1. Since the curves in figure 1 were computed for a high impurity concentration, the effects of heavy doping were included in the calculation. With respect to heavy doping, it has been shown (8) that for concentrations greater than 10¹⁷ cm⁻³, n_i must be replaced by an equivalent intrinsic concentration, n_{ie} , which is larger than n_i and varies with impurity concentration. For $N = 10^{20}$ cm⁻³, it is found that $n_{ie} = 12.96 n_i$ (8). Using the value 1.4x10¹⁰ cm⁻³ for n_i it follows that $n_{ie} = 1.81x10^{11}$ cm⁻³. It is clear, from the results of this computation, that Ta₂O₅ affords the advantage of greatly increased sensitivity in use of the MOS C-V technique.

Impurity Concentration

In the present case it will be seen that the impurity concentration N is determined at a depth approximately 10 Å from the diffused surface of the n⁺/p silicon solar cell. This is sufficiently close that N is considered to be a surface parameter.

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The impurity concentration is determined from the relation (9, 10),

$$N = \frac{2}{qc_s A^2} \frac{d(1/C_{HF}^2)}{dV} \quad (2)$$

A is the area of the MOS capacitor, V the applied voltage and C_{HF} is the MOS high frequency capacitance where

$$C_{HF} = \frac{C_o C_{sc}}{C_o + C_{sc}} \quad (3)$$

C_{sc} is the capacitance of the semiconductor space charge layer and C_o the oxide capacitance is given by

$$C_o = \frac{\epsilon_o A}{d} \quad (4)$$

Equation (2) is obtained using the depletion approximation (9, 10). In addition, the measurement frequency should be high enough so that interface states do not respond appreciably to the ac signal (9, 10).

In order to obtain numerical values of C_{HF} from equation (3) C_{sc} must first be obtained from the C-V data. If there were no losses in the MOS capacitor, then the measured capacitance would simply be a series combination of C_o and C_{sc} . However, in the present case, it is necessary to consider losses in the oxide and in the bulk semiconductor. The oxide losses are represented by a resistance R_o in parallel with C_o and bulk semiconductor losses by a resistance in series with C_{sc} . The high frequency equivalent circuit for the MOS capacitor, including these loss elements, is shown in figure 2. From the equivalent circuit, C_M , the measured capacitance is given by

$$C_M = \frac{C_{sc} [1 + (\omega R_o)^2 C_o (C_{sc} + C_o)]}{(1 - \omega^2 C_{sc} C_o R_o R_s)^2 + [C_{sc} (R_o + R_s) + \omega C_o R_o]^2} \quad (5)$$

Using measured values of C_M , C_{sc} can be obtained from equation (5) if C_o , R_o , and R_s are known. C_o and R_o are properties of the oxide and are obtained directly by measurement. To obtain R_s use is made of the fact that, at sufficiently high applied dc voltage, the semiconductor space charge region is in the strong accumulation condition. For an n-type semiconductor this implies a very high electron concentration near the surface and C_{sc} is effectively shorted out (11). This condition occurs at C_{sc}^{max} the maximum value of C_{sc} where;

$$C_{sc}^{max} = \frac{C_o R_o^2}{(R_o + R_s)^2 + (\omega C_o R_o)^2} \quad (6)$$

These relations yield the value of N at a distance W from the semiconductor surface, where

$$W = \frac{\epsilon_s A}{C_{sc}} \quad (7)$$

W being the width of the semiconductor space charge depletion region.

Charge in Surface and Oxide States

From the present experiment one obtains the quantity N_s , the density of charge, in both surface and oxide states, per unit surface area (12). N_s is determined from the well known technique (2) using the measured capacitance and voltage in the flat band condition, where

where

$$N_s = \frac{C_o}{Aq} (V_{FB} - \phi_{MS}) \quad (8)$$

where ϕ_{MS} is the difference in work function between the metal which forms one plate of the MOS capacitor and the semiconductor. V_{FB} is the value of the applied dc voltage at the flat band point, i.e., the voltage at which the flat band capacitance occurs. The latter is obtained from equation (5), using (2)

$$(C_{sc})_{FB} = Aq \left(\frac{C_o N_s}{kT} \right)^{1/2} \quad (9)$$

$(C_{sc})_{FB}$ being the capacitance of the semiconductor space charge region in the flat band condition.

EXPERIMENTAL PROCEDURE

The MOS C-V data were obtained using a 2 x 2 cm n⁺/p silicon solar cell of 10 ohm-cm base resistivity, obtained uncoated from the manufacturer. The Ta₂O₅ coating was deposited under a vacuum of 2x10⁻⁶ Torr. During vapor deposition, the Ta₂O₅ charge was contained in a water-cooled copper boat. The cell was mounted on a substrate which was heated to 300° C during deposition. The oxide deposition rate was 6.56 Å per second. Oxide thickness and index of refraction as determined by ellipsometry were 590 Å and 2.21, respectively. After oxide deposition, the cell had an AMO short circuit current of 140 ma and an open circuit voltage of 0.555 volts. The MOS capacitor was formed by vacuum depositing circular gold dots, 2.54x10⁻² cm in diameter, with a thickness of 2000 Å, as shown in figure 3. Contact to the gold dot was made by a gold wire probe using a micropositioner. The remaining electrical connection to the MOS capacitor was made to the Ag-Ti grid contact on the front face of the solar cell. This configuration was used in order to avoid the complicating effects of the p-n junction in the capacitance measurements. Capacitance as a function of applied dc voltage was determined with a Boonton 71 AR capacitance meter. Output of the capacitance meter was displayed on an x-y recorder. During measurement the solar cell was contained in a light-tight box into which an atmosphere of dry nitrogen gas was introduced.

RESULTS

The experimentally obtained C-V curve is shown in figure 4. Due to dielectric breakdown, applied dc voltages were limited to the range shown in the figure.

Impurity Concentration

The impurity concentration is evaluated from a plot of C_{sc}^{-2} vs V. However, R_s must first be obtained using (6). A reasonable estimate of C_{sc}^{max} is obtained by expanding the C-V data as shown in figure 5. The dotted line is an extrapolation based on previous experience with Ta₂O₅ coated-silicon MOS capacitors in this laboratory. C_o and R_o are obtained by measurement on a Ta₂O₅ coated - single crystal silicon, MOS capacitor in strong accumulation. With $C_o = 226.6$ pF, $R_o = 1.818 \times 10^3$ ohm, and $C_{sc}^{max} = 205.7$ pF it is found that $R_s = 79.1$ ohm.

A plot of C_{sc}^{-2} vs applied dc voltage is shown in figure 6. From the linear portion of the figure, it is found that

$$N = 2.9 \times 10^{20} \text{ cm}^{-3}$$

In addition it is found that W varies between 15.5 and 9.8 Å over the linear portion of figure 6. Hence the present work yields the impurity concentra-

tion at a minimum distance of 9.8 \AA from the diffused surface.

Charge in Surface and Oxide States

Using the above value for N , $(C_{sc})_{FB} = 2.212 \times 10^{-8} \text{ f}$, $(C_M)_{FB} = 204.3 \text{ pf}$, and $V_{FB} = 8.4$ volts. Using $\phi_{MS} = 0.9$ volt (13), it is found that

$$N_B = 2.1 \times 10^{13} \text{ cm}^{-2}$$

DISCUSSION

The configuration of figure 3 differs markedly from the geometry commonly utilized in MOS capacitors (2). Hence in showing feasibility it is necessary to calculate a theoretical C-V curve for comparison with the experimental data.

To compute a theoretical C-V curve one needs values of $(C_{sc})_T$, the theoretical value of the semiconductor space charge capacitance, where (14)

$$(C_{sc})_T = Aq \left(\frac{Nc_B}{2kT} \right)^{1/2} \frac{1 - e^{U_B}}{(e^{U_B} - 1 - U_B)^{1/2}} \quad (10)$$

with

$$U_B = \frac{q\psi_B}{kT} \quad (11)$$

ψ_B is the semiconductor surface potential at the diffused face. The values of $(C_{sc})_T$ obtained from equation (10) are substituted into equation (5) to obtain a calculated value for C_M . Since equation (10) does not include the response of interface states to the ac frequency $(C_{sc})_T$ is independent of these effects. Hence, in the absence of such response, the measured C-V curve should have the same shape as the calculated curve. This is seen to be the case in figure 7. The displacement between the two curves is due to the dc response of fixed surface and oxide charge (2).

The validity of the method used to obtain N is dependent on the validity of the depletion approximation (9, 10). In order to test the depletion assumption, Q_{sc} , the charge in the semiconductor space charge region is calculated using (14);

$$Q_{sc} = \pm (2Nc_B kT)^{1/2} \times \left[\left(\frac{n_{ie}}{N} \right)^2 (e^{-U_B} + U_B - 1) + (e^{U_B} - U_B - 1) \right]^{1/2} \quad (12)$$

Where Q_{sc} is positive or negative depending on whether ψ_B is negative or positive, respectively. The calculated curve is shown in figure 8. Also shown is the range covered by the present C-V data, where use has been made of the standard relation between applied voltage and surface potential (15). Examination of figure 8 shows that Q_{sc} varies as $\psi_B^{1/2}$ over the range covered by the C-V data. This is the behavior expected when the space charge region is in depletion and weak inversion (16). In the present case, the depletion region extends from $\psi_B = 0$ (Flat Band), to $\psi_B = -0.52$ volt. The latter surface potential corresponds to an applied voltage of -8.5 volts. Hence the linear portion of the C_{sc}^2 vs V plot lies almost entirely in the depletion region. Thus, it is demonstrated that the measured C-V curve behaves in accordance with MOS C-V theory and that the assumptions necessary for the validity of equation (2) are satisfied.

CONCLUSION

Because of the unconventional configuration used, consideration has been given to showing that the data behaves in accordance with MOS C-V theory. In addition it is found that the observed data lie largely in the depletion region of the semiconductor space charge layer. Furthermore, it is concluded that despite the high dopant concentration the MOS C-V technique yields useful information regarding the diffused surface of the solar cell.

This research represents the first successful application of the MOS C-V technique in obtaining information regarding the heavily doped, diffused face, of a silicon solar cell. For the cell investigated, it is found that U_B , the density of charge in surface and oxide states, has the value $2.1 \times 10^{13} \text{ cm}^{-2}$ and that the impurities concentration N has the value $2.9 \times 10^{20} \text{ cm}^{-3}$ at a minimum distance of 10 \AA from the diffused surface. This is sufficiently close that N is considered a surface parameter. Additional experimentation is required in order to separate the surface and oxide components from N_B . The surface component is directly related to surface recombination velocity (17) and would be useful when attempting to relate measurable surface parameters to solar cell efficiencies.

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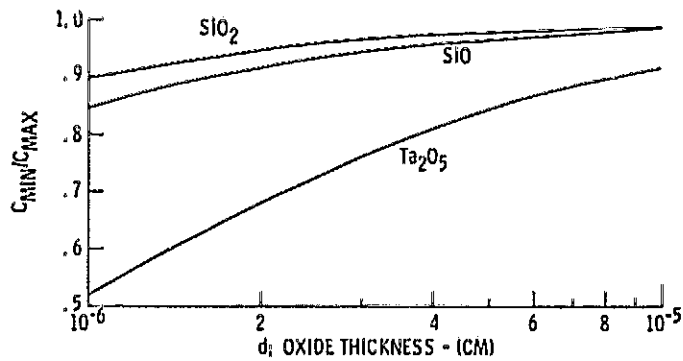


Figure 1. - C_{MIN}/C_{MAX} vs. oxide thickness. Numerical values used in Eq. (1) were: $\epsilon_0 = 2.66 \times 10^{-12}$, 3.4×10^{-13} , and 5.3×10^{-13} F/CM, for Ta_2O_5 , SiO_2 and SiO respectively. $N = 10^{20} \text{ CM}^{-3}$, $\epsilon_s = 1.06 \times 10^{-12}$ F/CM.

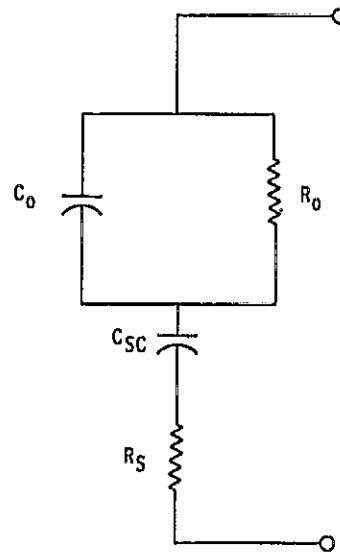


Figure 2. - High frequency equivalent circuit of MOS configuration.

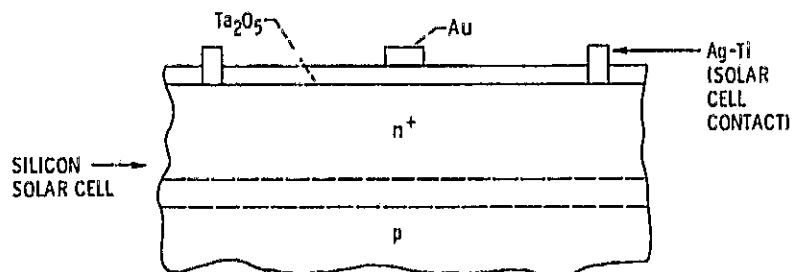


Figure 3. - MOS configuration used to obtain C-V data.

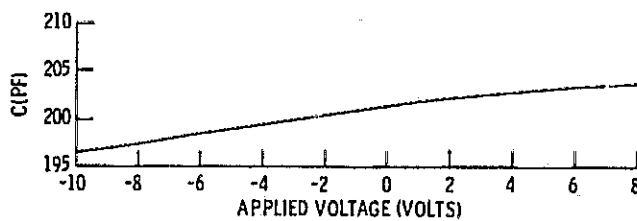


Figure 4. - C-V data obtained for diffused face.

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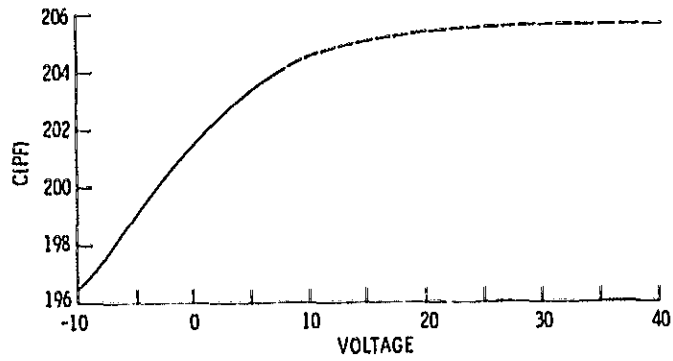


Figure 5. - Expanded C-V curve. Dotted line is extrapolation from measured curve.

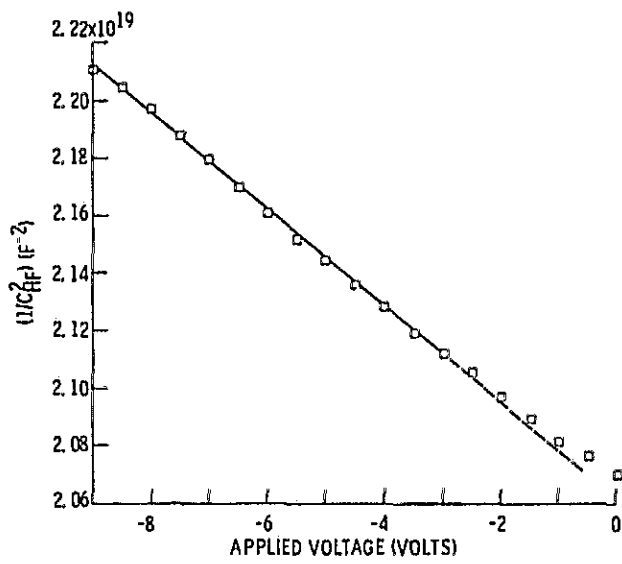


Figure 6. - $1/C_{HF}^2$ vs. applied d. c. voltage.

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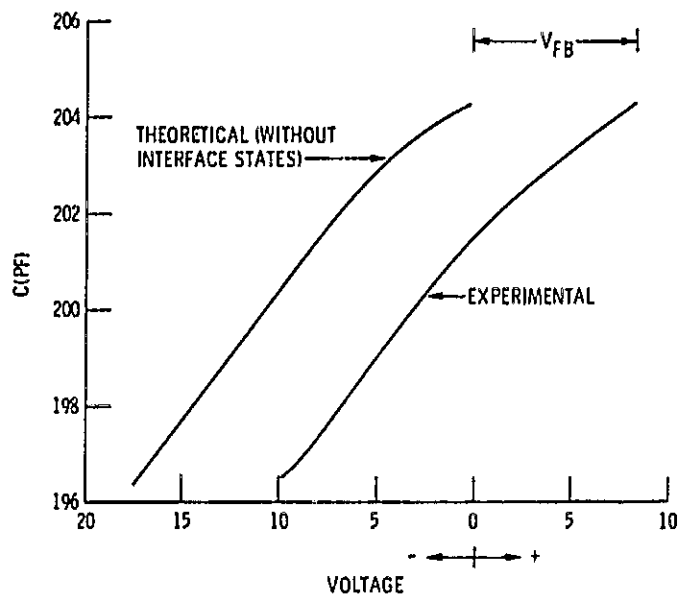


Figure 7. - Experimental and theoretical curves. V_{FB} is the flat band voltage.

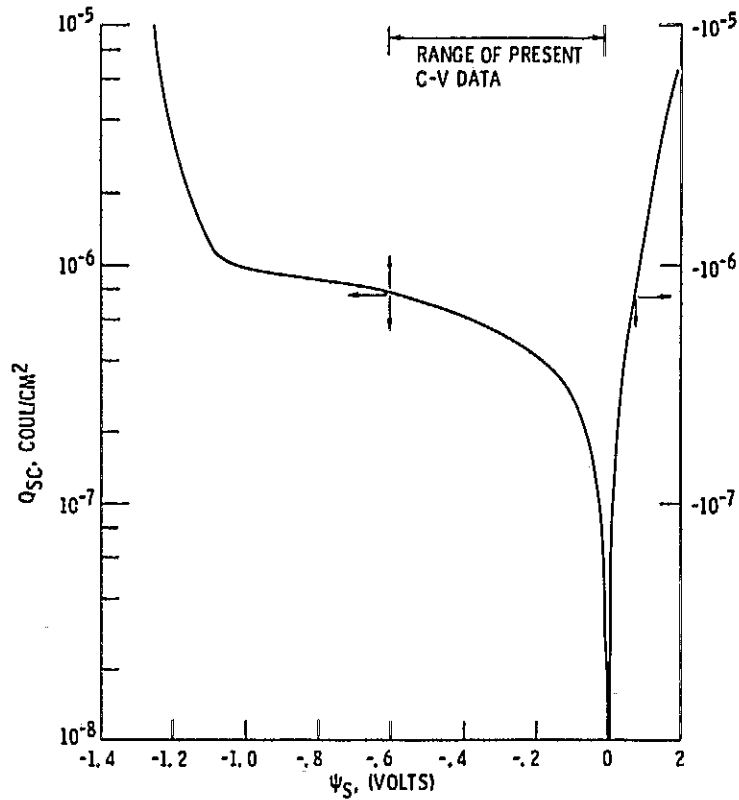


Figure 8. - Charge in semiconductor space charge region vs. surface potential, Ψ_S .

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