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

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ABSTRACT

The NOS C-V technique has been widely used, with SiO2 as the oxide, to determine surface state parameters on silicon with carrier concentrations less than 10^{18} cm^{-3}. However, at higher impurity concentrations, especially those encountered on the p⁺ solar cell surface (N > 10^{18} cm^{-3}), the NOS 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 NOS C-V technique to obtain information regarding 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 \AA \text{ from the diffused surface, has the value 2.9x10^{10} cm^{-3}. In} addition, it is found that Np, the density of charge in surface oxide states has the value 2.1x10^{13} 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 NOS C-V technique yields useful information concerning surface parameters which contribute to the high, efficiency limiting, surface recombination velocities on the p⁺ 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 10^{18} cm^{-3}. This limitation arises from the fact that the sensitivity of the technique decreases with increasing carrier concentration. However, concentrations in the 10^{18} 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 assertion. For the present, it is noted that the properties of the p⁺-n/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 NOS 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 formulas 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 NOS C-V technique varies inversely with \( \frac{C_{\text{min}}}{C_{\text{max}}} \) 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).

\[
\frac{C_{\text{min}}}{C_{\text{max}}} = \frac{1}{1 + \frac{2\pi}{C_{\text{d}}^{2}N_{d}N_{i}kT}}
\]

where \( C_{d} \) 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, \( N_{d} \) the intrinsic carrier concentration, \( N_{i} \) the intrinsic concentration, \( q_{d} \) the intrinsic concentration, \( N_{d} \) the intrinsic concentration, \( T \) the sensitivity increases for \( q_{d} \)

Impurity Concentration

In the present case it will be seen that the impurity concentration \( N \) is determined at a depth approximately 10 \AA \text{ from the diffused surface at the p⁺/n+ silicon solar cell. This is sufficiently close that } N \text{ is considered to be a surface parameter.
The impurity concentration is determined from the relation (9, 10),

\[ N = \frac{2}{q \varepsilon_a a^2} \left( \frac{1}{C_{\text{FB}}} \right) \frac{d}{dV} \]

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 \( C_{\text{FB}} \) from equation (3) \( C_{\text{BC}} \) 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 \( C_0 \) and \( C_{\text{BC}} \). 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 \( R_L \) in parallel with \( C_0 \) and bulk semiconductor losses by a resistance in series with \( C_{\text{BC}} \). The high frequency equivalent circuit for the MOS capacitor, including these loss elements, is shown in figure 2.

From the equivalent circuit, \( C_{\text{FH}} \) is given by

\[ C_{\text{FH}} = \frac{C_0 C_{\text{BC}}}{C_0 + C_{\text{BC}}} \]

Using measured values of \( C_{\text{FH}} \), \( C_{\text{BC}} \) can be obtained from equation (5) if \( C_0 \), \( R_L \), and \( R_B \) are known. \( C_0 \) and \( R_L \) are properties of the oxide and are obtained directly by measurement. To obtain \( R_B \), 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 \( C_0 \) is effectively shunted out (11). This condition occurs at \( C_{\text{MAX}} \) the maximum value of \( C_0 \) where

\[ C_{\text{MAX}} = \frac{C_0 R_B^2}{(R_B + R_0)^2 + 4 C_0 R_B R_0} \]

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

\[ W = \frac{C_0 a^2}{C_{\text{BC}}} \]

where

\[ W = \frac{C_0 a^2}{C_{\text{BC}}} \]
tion at a minimum distance of 9.8 Å from the diffused surface.

**Charge in Surface and Oxide States**

Using the above value for \( N \), (\( C_{oc} \))_{T} has been made. of the standard relation between applied volt-

\[ Q_{sc} \] is the semiconductor surface potential at the diff-

The validity of the method used to obtain \( N \) is de-

\[ Q_{oc} \] is the charge in the semiconductor space charge

where \( \phi_{b} \) is the semiconductor surface potential at the dif-

\[ N_{a} = 2.1 \times 10^{13} \text{ cm}^{-2} \]


**CONCLUSION**

Because of the unconventional configuration used, consideration has been given to showing that the data be-

This research represents the first successful ap-

\[ Q_{sc} \] is positive or negative depending on whether \( \psi_{d} \) is nega-

\[ U_{b} = \frac{\psi_{b}}{kT} \]

\[ 
\begin{align*}
\frac{Q_{oc}}{N} &= \frac{1}{2} \frac{U_{b}}{kT} \left( \frac{U_{b} - U_{a}}{U_{b} - U_{a}} \right)^{1/2} \\
&= \frac{1}{2} \frac{U_{b}}{kT} \left( \frac{U_{b} - U_{a}}{U_{b} - U_{a}} \right)^{1/2} \end{align*}
\]

**REFERENCES**


Figure 1. - $C_{MIN} C_{MAX}$ vs. oxide thickness. Numerical values used in Eq. (1) were: $E_0 = 2.6x10^{-12}$, $8.4x10^{-12}$, and $5.3x10^{-13}$ F/cm, for Ta$_2$O$_5$, SiO$_2$, and SiO respectively. $N = 10^{20}$ CM$^{-3}$, $e_0 = 1.06x10^{-12}$ F/cm.$^2$.

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

Figure 6. - $1/C^2$ vs. applied d.c. voltage.
Figure 1. Experimental and theoretical curves. \( V_{FB} \) is the flat band voltage.

Figure 2. Charge in semiconductor space charge region vs. surface potential, \( \Psi_S \).