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DISTRIBUTION OF FLATBAND VOLTAGES IN LATERALLY NONUNIFORM MIS CAPACITORS AND APPLICATION TO A TEST FOR NONUNIFORMITIES

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The effect of a laterally nonuniform distribution of fixed charge in the insulator of an MIS capacitor can be characterized by a flatband-voltage distribution function. We present a simple, approximate C-V method for determining this distribution, and apply the result to a test for distinguishing between interface states and laterally nonuniform fixed charge. Examples are presented.

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DISTRIBUTION OF FLATBAND VOLTAGES IN LATERALLY NONUNIFORM MIS CAPACITORS AND APPLICATION TO A TEST FOR NONUNIFORMITIES

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ABSTRACT

Interface states and lateral nonuniformities produce very similar abnormalities in the C-V curves of MIS capacitors. The effect of a laterally nonuniform distribution of fixed charge in the insulator can be characterized by a flatband-voltage distribution function. Here we present a simple, approximate method for determining this distribution from the quasi-static and high-frequency C-V curves of the capacitor, and we apply the result to a test for distinguishing between interface states and laterally nonuniform fixed charge. The test is based on a principle that is implicit in the results of an analysis previously published by Brews and Lopez, namely that interface states and lateral nonuniformities cannot produce identical distortions in both the quasi-static and high-frequency C-V curves. The presence of either lateral nonuniformities or interface states can be tested by assuming all C-V distortions to be due to the other cause. The C-V curves are regenerated under this assumption, and discrepancies between the measured and regenerated curves indicate the presence of the effect assumed not to be present.

I. INTRODUCTION

It is well known that interface states and lateral nonuniformities produce very similar abnormalities in the capacitance-voltage (C-V) curves of metal-insulator-semiconductor (MIS) capacitors. The departures from normal consist of a stretch-out along the voltage axis of both the high-frequency and low-frequency C-V characteristics, together with abnormally large values of low-frequency capacitance in the region corresponding to the depletion regime of a uniform MIS structure [1]. It is often important to establish the cause of a particular C-V abnormality and to characterize the effect properly. The characterization of interface states can be done by any one of a number of very effective methods which are so well known that they do not require documentation here. The identification and characterization of lateral nonuniformities are in a less satisfactory state. Nicollian and Goetzberger [2] have shown that *lateral nonuniformities* produce a broadening of the a-c conductance vs. frequency characteristic in the depletion regime. Brews and Lopez [3] have shown that lateral nonuniformities lead to a calculated doping profile in the semiconductor that is different from the actual profile. In a previous paper [4], we have discussed frequency and temperature tests for distinguishing between lateral nonuniformities and interface states. As for the characterization of lateral nonuniformities, Nicollian and Goetzberger [2] and Castagne and Vapaille [5] assumed a random lateral dispersal of charge in the insulator and described the nonuniformity in terms of a Gaussian density function having a single adjustable parameter: the statistical variance of the distribution. The assumption, however, of a random dispersal of charge is not always suitable, as has been demonstrated by DiStefano [6] and Williams and Woods [7], whose photoemission experiments showed that sodium ions tend to form localized clusters at the $Si-SiO_2$ interface in an MOS capacitor.

In this paper we first present a simple, although approximate, C-V method for determining the distribution of flatband voltages in an MIS capacitor that has a laterally nonuniform, but not necessarily random, distribution of fixed charge in the insulator. We then show how this method can be used in connection with the room-temperature high-frequency and low-frequency C-V curves to test for lateral nonuniformities and interface states. The model that we use for a laterally nonuniform MIS capacitor consists of a parallel set of small, noninteracting capacitors, each of which can be considered to be uniform over its area. As Brews [8] has pointed out, this model will not provide a satisfactory representation for lateral nonuniformities of very small dimensions. The minimum size allowed of a lateral nonuniformity for adequate representation by the parallel-array model is roughly equal to the smaller of the insulator and depletion layer thicknesses [8], and our analysis is subject to this limitation.

II. DETERMINATION OF FLATBAND VOLTAGE DISTRIBUTION

We restrict our attention at this point to MIS capacitors which have laterally nonuniform distributions of fixed charge in the insulator but which are otherwise uniform, and which have negligible interface states. Using the parallel-array model of small capacitors, the lateral nonuniformity can be characterized by a flatband-voltage distribution function, $f(V_{FB})$, such that $f(V_{FB})\, dV_{FB}$ is the fraction of the small capacitors that have flatband voltages in the range from V_{FB} to $V_{FB} + dV_{FB}$. The objective will be to devise a method for determining $f(V_{FB})$ from the measured low-frequency (quasi-static) and high-frequency C-V curves. The problem is mathematically intractable unless some approximation is made, and the approximation we have chosen can be understood with the aid of Fig. 1. Figure 1(a) shows typical curves of quasi-static capacitance, C_{QS}, and high-frequency capacitance, C_{HF}, plotted against field-plate, or "gate", voltage, V_G, for an ideal, uniform MIS structure with negligible interface states. The flatband voltage of the capacitor is nonzero and is denoted by V_o. The voltage difference denoted by V_T is the conventionally defined turn-on voltage of an ideal MIS capacitor having the same insulator thickness and substrate doping but with zero flatband voltage [9],[10]. (The curves of Fig. 1 are drawn to relative scale for a p-Si MOS capacitor with a uniform substrate doping of 5×10^{15} cm^{-3}, an oxide thickness of 1000 Å, and a flatband voltage of 1.4 V.) In Fig. 1(b) is plotted the difference between the quasi-static and high-frequency capacitance functions, $\Delta C(V_G) = C_{QS} - C_{HF}$, and Fig. 1(c) shows the distribution of flatband voltages, $f(V_{FB})$, which, for this capacitor, is a delta function of unit area located at V_o on the V_{FB} axis. As is shown in Fig. 1(b), the capacitance-difference function, $\Delta C(V_G)$, is quite small for $V_G < V_o + V_T$, but rapidly approaches the constant value ΔC_{max} for $V_G > V_o + V_T$. The approximation that we shall make is that $\Delta C(V_G)$ for this capacitor can be represented with sufficient accuracy by a step function: $\Delta C(V_G) = 0$ for $V_G < V_o + V_T$, and $\Delta C(V_G) = \Delta C_{max}$ for $V_G > V_o + V_T$.

The application of the foregoing approximation to a nonuniform MIS capacitor without interface states is illustrated in Fig. 2. In Fig. 2(a) are shown the stretched-out quasi-static and high-frequency curves of the capacitor. The capacitance difference, $\Delta C = C_{QS} - C_{HF}$, is plotted in Fig. 2(b). Figure 2(c) shows the distribution of flatband voltages,

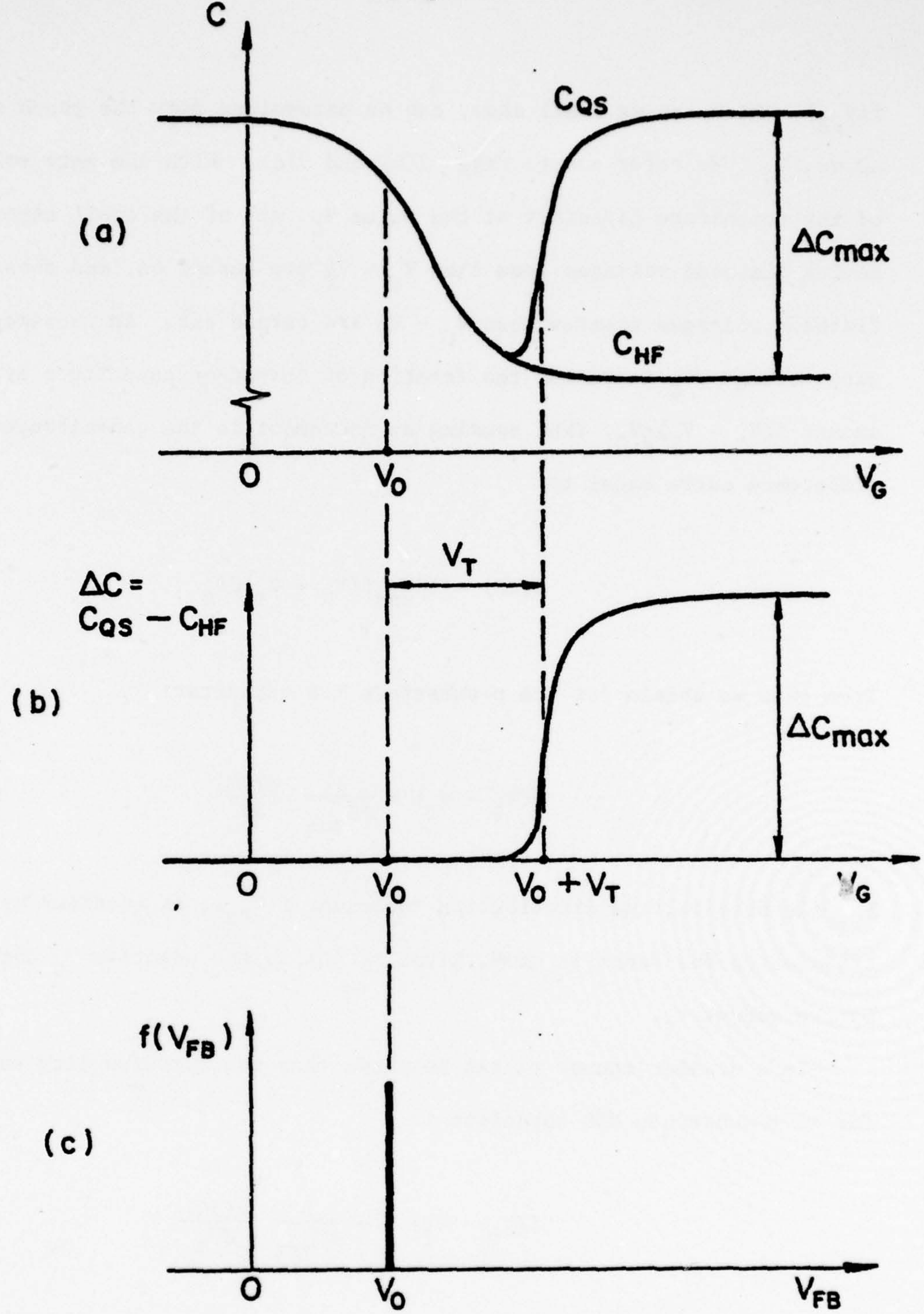

Fig. 1. (a) Typical *quasi-static* and high-frequency C-V curves for a uniform MIS capacitor with negligible interface states. The flatband voltage is denoted by V_0. (b) The capacitance-difference function, $\Delta C = C_{QS} - C_{HF}$, which will be approximated by a step function in the analysis. The voltage V_T is the conventionally defined turn-on voltage of the capacitor. (c) The distribution of flatband voltages for this capacitor — a delta function of unit area located at V_0.

$f(V_{FB})$, which, as we shall show, can be determined from the graph of ΔC vs. V_G. We refer now to Figs. 2(b) and 2(c). With the gate voltage of the nonuniform capacitor at the value V_G, all of the small capacitors having flatband voltages less than $V_G - V_T$ are turned on, and those having flatband voltages greater than $V_G - V_T$ are turned off. An increment of gate voltage dV_G increases the fraction of turned-on capacitors by the amount $f(V_G - V_T)dV_G$, thus causing an increment in the capacitance-difference curve equal to

$$d(\Delta C) = \Delta C_{max} f(V_G - V_T) dV_G \ . \tag{1}$$

From this we obtain for the p-substrate MIS capacitor:

$$f(V_G - V_T) = \frac{1}{\Delta C_{max}} \frac{d(\Delta C)}{dV_G} \tag{2}$$

The flatband-voltage, distribution function, $f(V_{FB})$, is obtained by translating the function of V_G given by (2) in the negative V_G direction by the amount V_T.

In a similar manner it can be shown that the corresponding expression for an n-substrate MIS capacitor is

$$f(V_G - V_T) = -\frac{1}{\Delta C_{max}} \frac{d(\Delta C)}{dV_G} \tag{3}$$

where V_T is now a negative voltage and $f(V_{FB})$ is therefore obtained by translating the result of (3) in the positive V_G direction by the amount $|V_T|$.

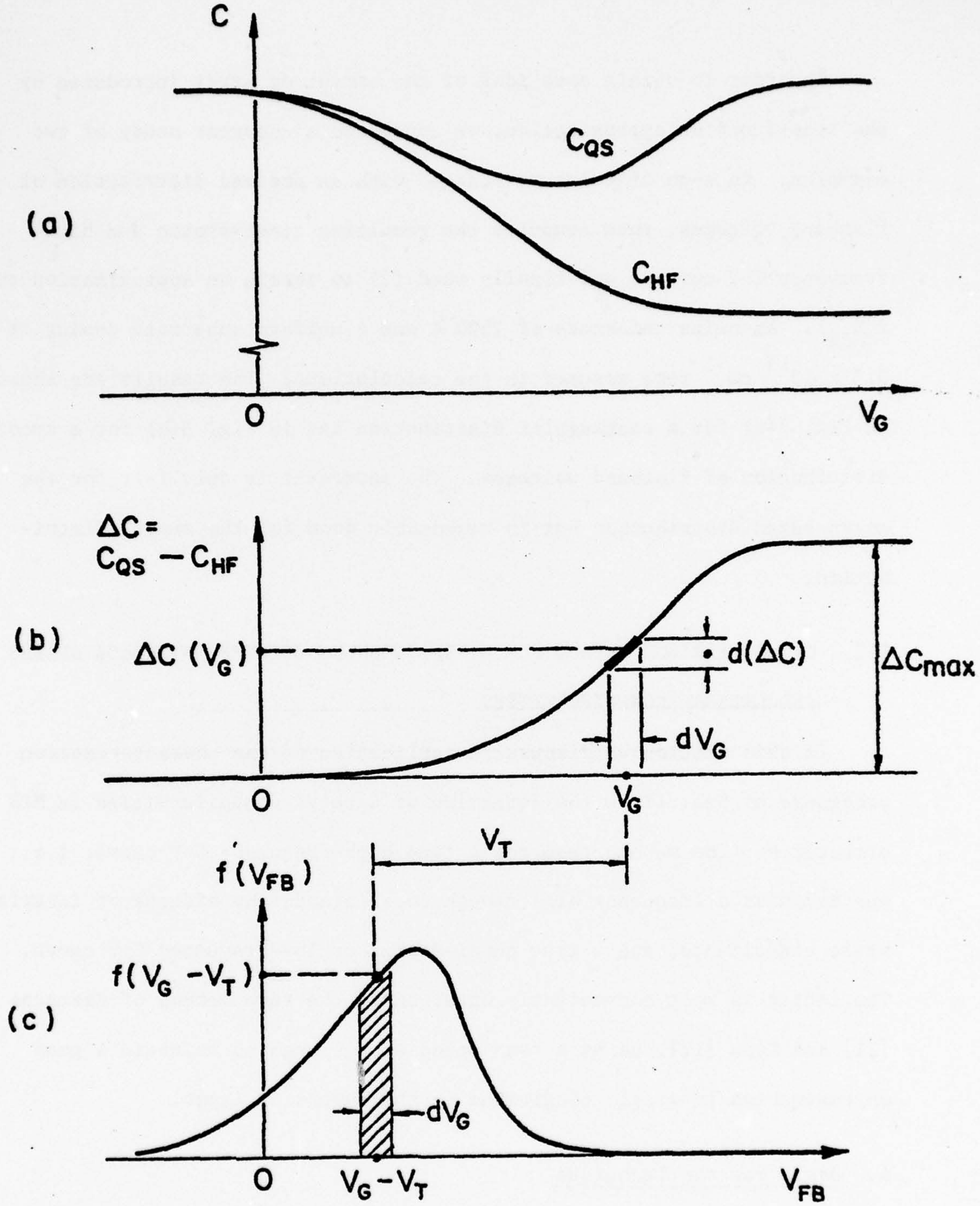

Fig. 2. (a) Quasi-static and high-frequency C-V curves of an MIS capacitor having a laterally nonuniform fixed charge in the insulator. (b) The capacitance-difference function, ΔC. (c) The flatband-voltage distribution function, $f(V_{FB})$.

In order to obtain some idea of the amount of error introduced by the step-function approximation, we conducted a computer study of two examples. In each of these we started with an assumed distribution of flatband voltages, then computed the resulting quasi-static and high-frequency C-V curves, and finally used (2) to obtain an approximation to $f(V_{FB})$. An oxide thickness of 2500 Å and a uniform substrate doping of 3.3×10^{15} cm^{-3} were assumed in the calculations. The results are shown in Fig. 3(a) for a rectangular distribution and in Fig. 3(b) for a smooth distribution of flatband voltages. The agreement is only fair for the sharp-edged distribution but is reasonably good for the smooth distribution.

III. C-V COMPARISON METHOD FOR DISTINGUISHING BETWEEN INTERFACE STATES AND LATERAL NONUNIFORMITIES

In this section we discuss an application of the characterization procedure of Sec. II to the detection of *lateral nonuniformities in* MIS structures. The method requires a true high-frequency C-V curve, i.e., one taken at a frequency high enough to eliminate the effects of interface-state capacitance, and a true quasi-static or low-frequency C-V curve. The latter is most conveniently obtained by the ramp method of Castagne [11] and Kuhn [12], using a ramp speed slow enough to maintain a good approximation to static conditions in the inversion layer.

A. Basis for the Technique

For this purpose we adapt an analysis originally given by Brews and Lopez [3] which they devised to show that lateral nonuniformities affect the surface-potential dependence of the depletion width. We first define an apparent surface potential, ψ_{app}, by means of a relationship

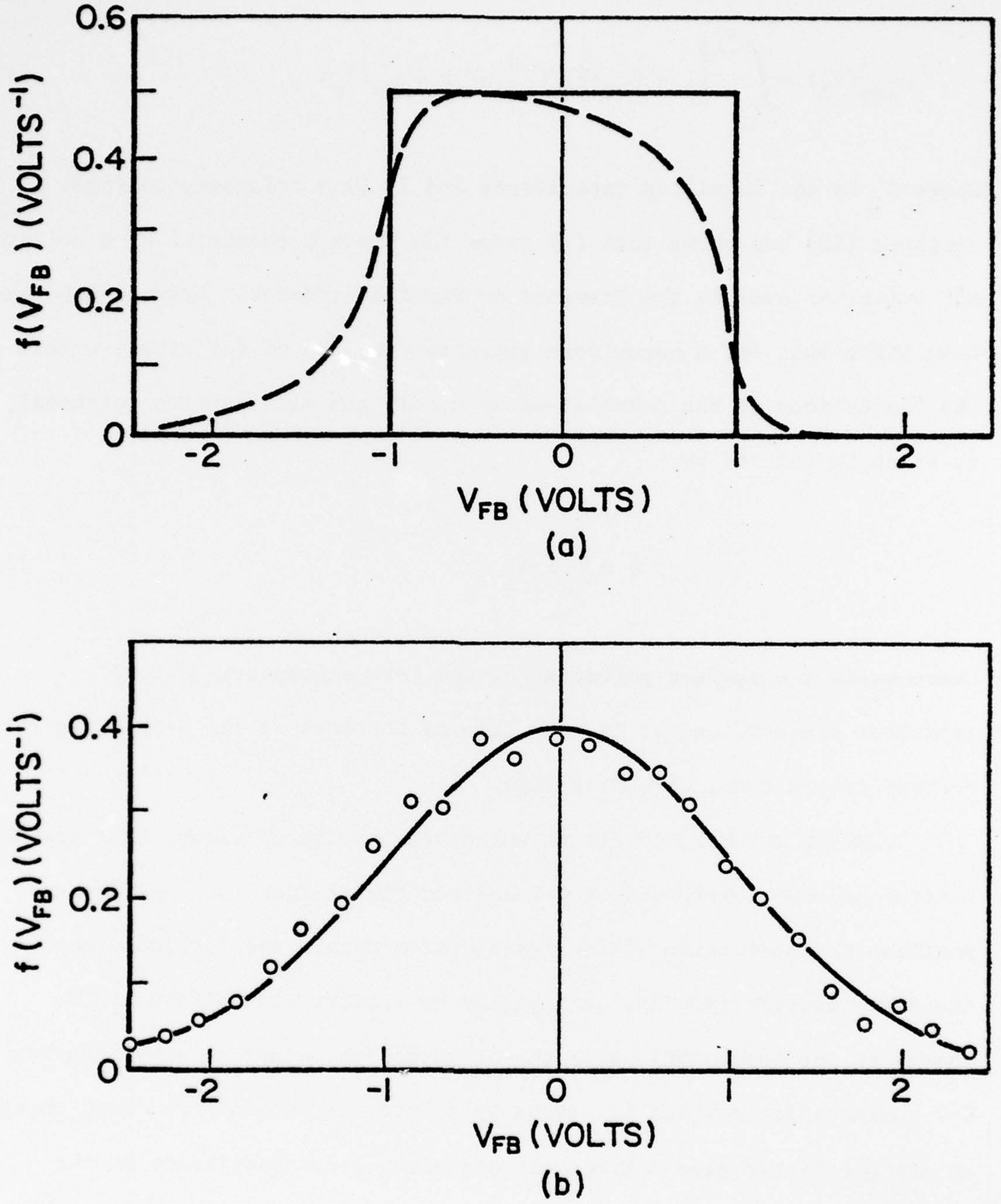

Fig. 3. Results of a computer study of errors introduced by the step-function approximation. Solid curves: distribution functions originally assumed. Dashed curve (a) and circles (b): computed from $\Delta C(V_G)$ by use of (2).

derived by Berglund [13]:

$$\psi_{app}(V_G) = \int_{V_o}^{V_G} \left[1 - C_{QS}(V)/C_i\right] dV + \psi_{app}(V_o) , \tag{4}$$

where C_i is the insulator capacitance and V_o is a reference voltage. Berglund [13] has shown that (4) gives the surface potential of a uniform MIS capacitor even in the presence of interface states. Brews and Lopez [3] have shown that for a nonuniform capacitor the use of (4) gives, within the limitations of the parallel-array model, the mean surface potential, $\bar{\psi}$, which is defined by

$$\bar{\psi} = \sum_j \alpha_j \psi_j , \tag{5}$$

where ψ_j is the surface potential of the j-th elementary uniform capacitor element, and α_j is the ratio of the area of the j-th capacitor element to the total capacitor area.

Consider two MIS capacitors which are identical except that one has a stretched-out low-frequency C-V characteristic that is caused by a particular distribution of interface states within the forbidden gap of the semiconductor (perhaps accompanied by a laterally uniform fixed charge in the insulator) while the other has an identical low-frequency C-V characteristic which is caused by a laterally nonuniform fixed charge. At any particular gate voltage the high-frequency capacitance of the j-th capacitor element in the nonuniform capacitor is given by $A_j C_{HF}(\psi_j)$, where $C_{HF}(\psi_j)$ is the high-frequency capacitance per unit area at the surface potential ψ_j, and A_j is the area of the j-th capacitor. The total high-frequency capacitance per unit area is given by the sum

$$C_{HF(LN)} = \sum_j \alpha_j C_{HF}(\psi_j) , \qquad (6)$$

where the additional subscript (LN) indicates the laterally nonuniform capacitor.

For the laterally uniform capacitor, one can imagine the surface to be divided into elements identical with those used for the nonuniform capacitor, in which case the surface potential at the particular gate voltage can be written in the form of (5), where $\bar{\psi}$ is now the actual, uniform, value of surface potential at the particular gate voltage. For the uniform capacitor with interface states, then, we can write the high-frequency capacitance as

$$C_{HF(IS)} = C_{HF}\left(\sum_j \alpha_j \psi_j\right) , \qquad (7)$$

where the additional subscript (IS) indicates the capacitor with interface states. In view of the well known nonlinearity of the relationship between C_{HF} and the surface potential, comparison of (6) with (7) shows that the high-frequency capacitances of the nonuniform capacitor and the capacitor with interface states will be unequal. Consequently we can state the following principle:

> When a C-V abnormality is caused by laterally nonuniform fixed charge in the insulator, the resulting quasi-static and high-frequency C-V curves cannot both be fitted by any distribution of interface states, and, conversely, if the C-V abnormality is caused by interface states, the resulting quasi-static and high-frequency C-V curves cannot both be fitted by any lateral distribution of flatband voltages.

B. C-V Comparison Method

A convenient method of utilizing the foregoing principle is to perform a combination of two tests, as follows:

1. Test for interface states by assuming the opposite, i.e., assume that the C-V abnormality is entirely due to laterally nonuniform fixed charge. Then: (a) determine the distribution of flatband voltages from the measured quasi-static and high-frequency C-V curves by the method described in Sec. II; (b) using this hypothetical distribution of flatband voltages, regenerate the two C-V curves by computer; and (c) compare the regenerated curves with the measured curves. A discrepancy will indicate the presence of interface states.

2. Test for lateral nonuniformity by assuming the opposite, i.e., assume that the C-V abnormality is entirely due to interface states. Then (a) obtain the surface potential $\psi(V_G)$ by use of Berglund's relation (4); (b) from this result compute the corresponding high-frequency characteristic $C_{HF}(V_G)$; and (c) compare the computed C_{HF}-V_G curve with the measured C_{HF}-V_G curve. A mismatch between the two will indicate the presence of lateral nonuniformities.

C. Examples

Two examples will be presented, one for an MIS capacitor in which substantial concentrations of interface states had been generated by high-field stress, and the other for a capacitor that had been bombarded with a nonuniform electron beam which produced a laterally nonuniform fixed charge in the insulator.

Example 1: For this example we tested the same high-field-stressed MOS capacitor that was used for Example 1 of Reference 4, where a frequency-dispersion test indicated that the C-V abnormalities introduced by the high-field stressing were caused by interface states that had not been present in the fresh sample. Also, this capacitor was similar to the one used for Example 3 of Reference 4, where a low-temperature test performed after high-field stressing pointed to the same conclusion. The capacitor had an n-type silicon substrate with a resistivity of 1.6 Ω·cm, an HCl-steam grown SiO_2 insulator with a thickness of 2560 Å, and an aluminum field plate. The C-V curves of the sample before stressing were nearly ideal in shape and were consistent with a uniform substrate doping of 3.0×10^{15} cm^{-3}. The original flatband voltage was approximately -0.5 V. The insulator was subjected to high-field stress by applying -175 V to the field plate for 10 h at room temperature (average field in the oxide approximately 6.8 MV/cm). The room-temperature quasi-static and high-frequency (1 MHz) C-V characteristics after this treatment are shown by the solid curves of Fig. 4. The curves are stretched out and the quasi-static capacitance is considerably greater than the 1-MHz capacitance in the depletion regime.

We tested for the presence of interface states by assuming the opposite condition, i.e., only lateral nonuniformity. By use of (3) we computed the hypothetical distribution of flatband voltages that would be required to account for the observed $\Delta C(V_G) = C_{QS} - C_{HF}$ shown by the solid curves of Fig. 4. This produced the result given in Fig. 5. The hypothetical distribution of flatband voltages was then used in a computer regeneration of the quasi-static and high-frequency C-V curves,

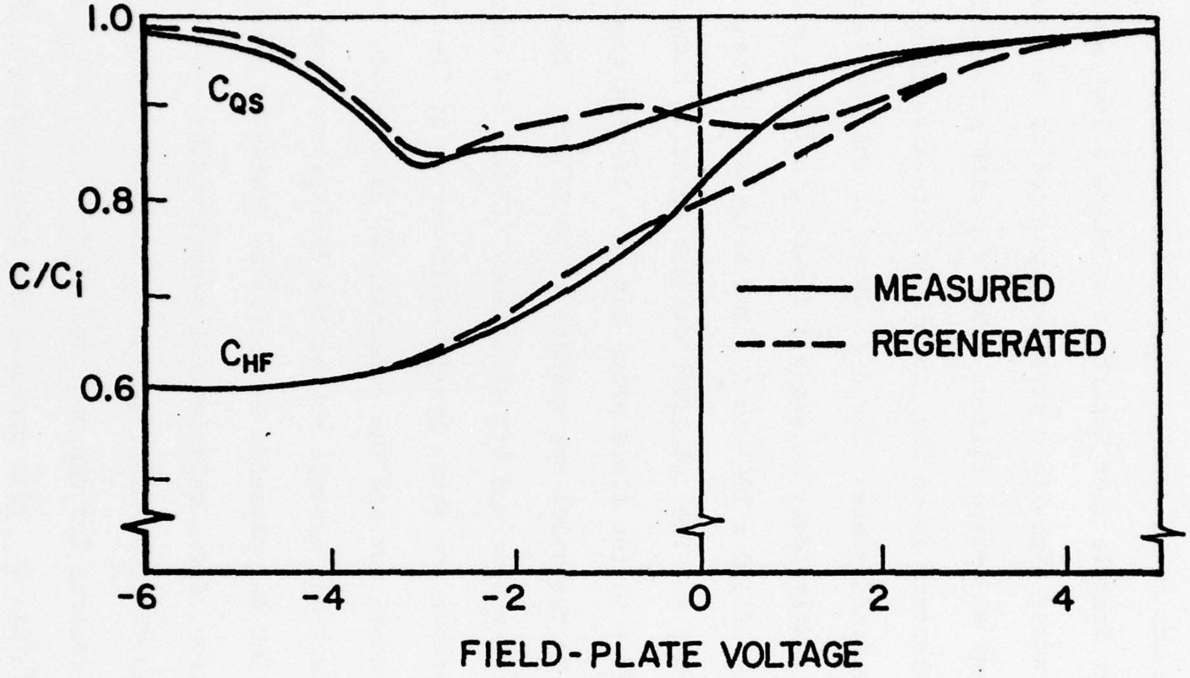

Fig. 4. C-V curves for interface-state test of Example 1. Solid curves: Measured after high-field stress. Dashed curves: Computed from hypothetical distribution of flatband voltages (Fig. 5). The discrepancies show the presence of interface states.

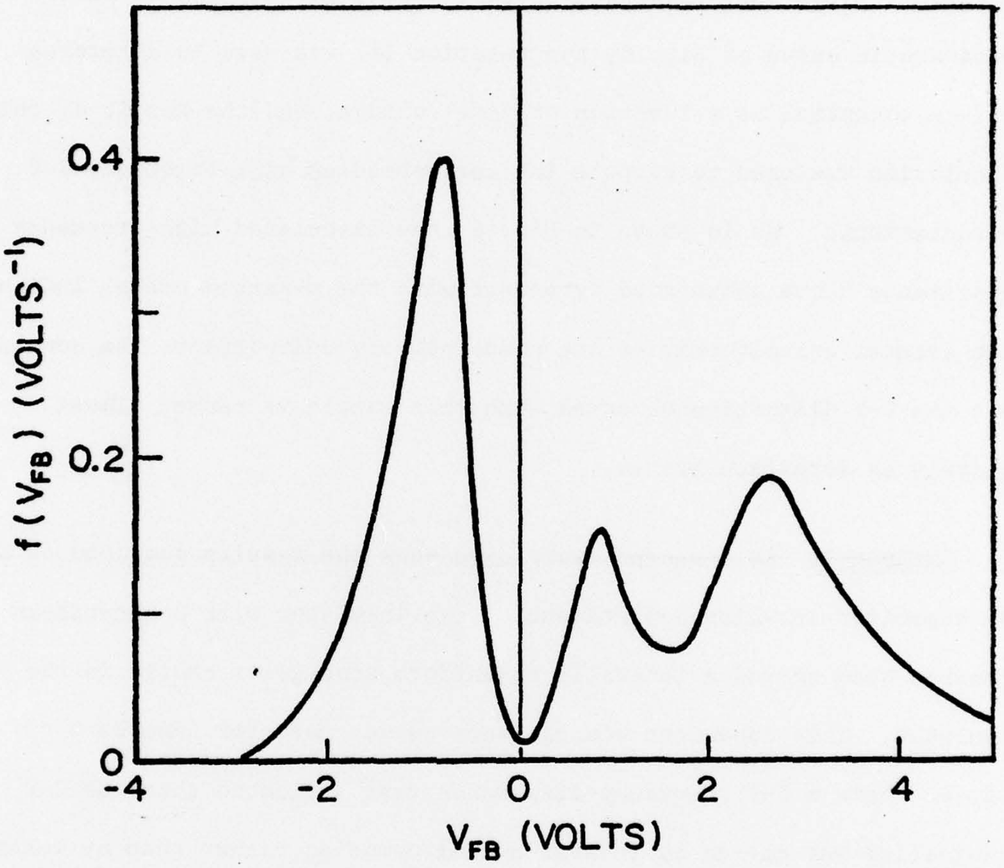

Fig. 5. Hypothetical distribution of flatband voltages derived from the measured C-V curves of Fig. 4 and used as the basis for the computer-regenerated (dashed) curves of that figure.

yielding the results shown by the dashed curves of Fig. 4. The considerable mismatch between these and the measured curves indicates the presence of substantial concentrations of interface states.

Next, we tested for lateral nonuniformity by assuming the opposite condition, i.e., only interface states. Starting with the measured quasi-static curve of Fig. 4, the relation (4) was used to determine surface potential as a function of gate voltage, and the result of this calculation was used to compute the corresponding high-frequency C-V characteristic. As is shown in Fig. 6, the calculated high-frequency capacitance curve shows good agreement with the measured curve, indicating that lateral nonuniformities are comparatively unimportant. We conclude that the C-V distortion observed with this sample is caused almost entirely by interface states.

Example 2: As a second example we show the results obtained on an MOS capacitor in which bombardment of the insulator with a nonuniform electron beam caused a laterally nonuniform storage of charge in the insulator. This capacitor was the same as was used for Example 2 of Ref. 4, where a C-V frequency-dispersion test indicated that the C-V abnormality was caused by lateral nonuniformities rather than by interface states. The sample had an n-type silicon substrate with a resistivity of 3-5 Ω·cm, an SiO_2 insulator which was thermally grown in dry oxygen to a thickness of 4700 Å, and an aluminum field plate. The sample, with field plate positive, had been bombarded with a 4.5-keV electron beam, after which the sample was annealed at 350°C for 1 h. The quasi-static and high-frequency (1 MHz) characteristics after this treatment are shown by the solid curves of Fig. 7(a).

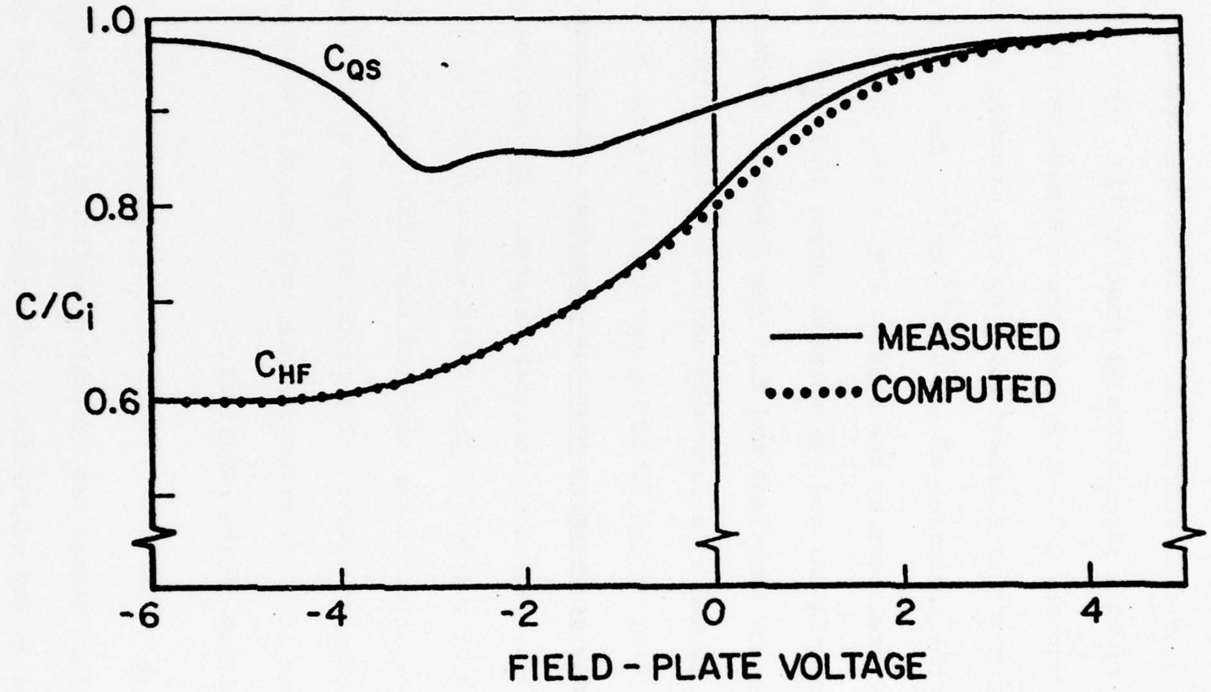

Fig. 6. C-V curves for lateral-nonuniformity test of Example 1. Solid curves: Measured (same as in Fig. 4). Dotted curve: High-frequency curve computed from quasi-static curve assuming only interface states. Correspondence with the measured curve indicates that lateral nonuniformities are unimportant.

We first tested for interface states by assuming that the C-V abnormality was caused entirely by lateral nonuniformity. By use of (3) we computed the hypothetical distribution of flatband voltages that would be required to account for the difference between C_{QS} and C_{HF}. The result of this calculation is shown in Fig. 7(b). The quasi-static and high-frequency C-V curves were then regenerated by computer, using this distribution of flatband voltages and assuming a uniform doping density in the substrate of 1.2×10^{15} cm^{-3}. The results of this computation are shown by the dots in Fig. 7(a). The excellent agreement between the original and regenerated curves indicates that interface states were not important and that the observed distortion of the C-V curves was caused by a laterally nonuniform fixed charge in the insulator.

As a check of the foregoing conclusion, we tested for lateral nonuniformity by assuming that the capacitor was uniform and the C-V distortion was caused by interface states. The surface potential was computed as a function of gate voltage by use of (4), and the high-frequency capacitance was computed from this, assuming the same substrate doping density as before. The result is shown by the dashed curve in Fig. 8. The lack of correspondence confirms the presence of lateral nonuniformities in the capacitor.

IV. SUMMARY

Interface states and lateral nonuniformities produce very similar distortions in the quasi-static and high-frequency C-V curves of MIS capacitors. In this paper we have proposed two C-V techniques relating to this problem: (1) a method for determining the distribution of flatband

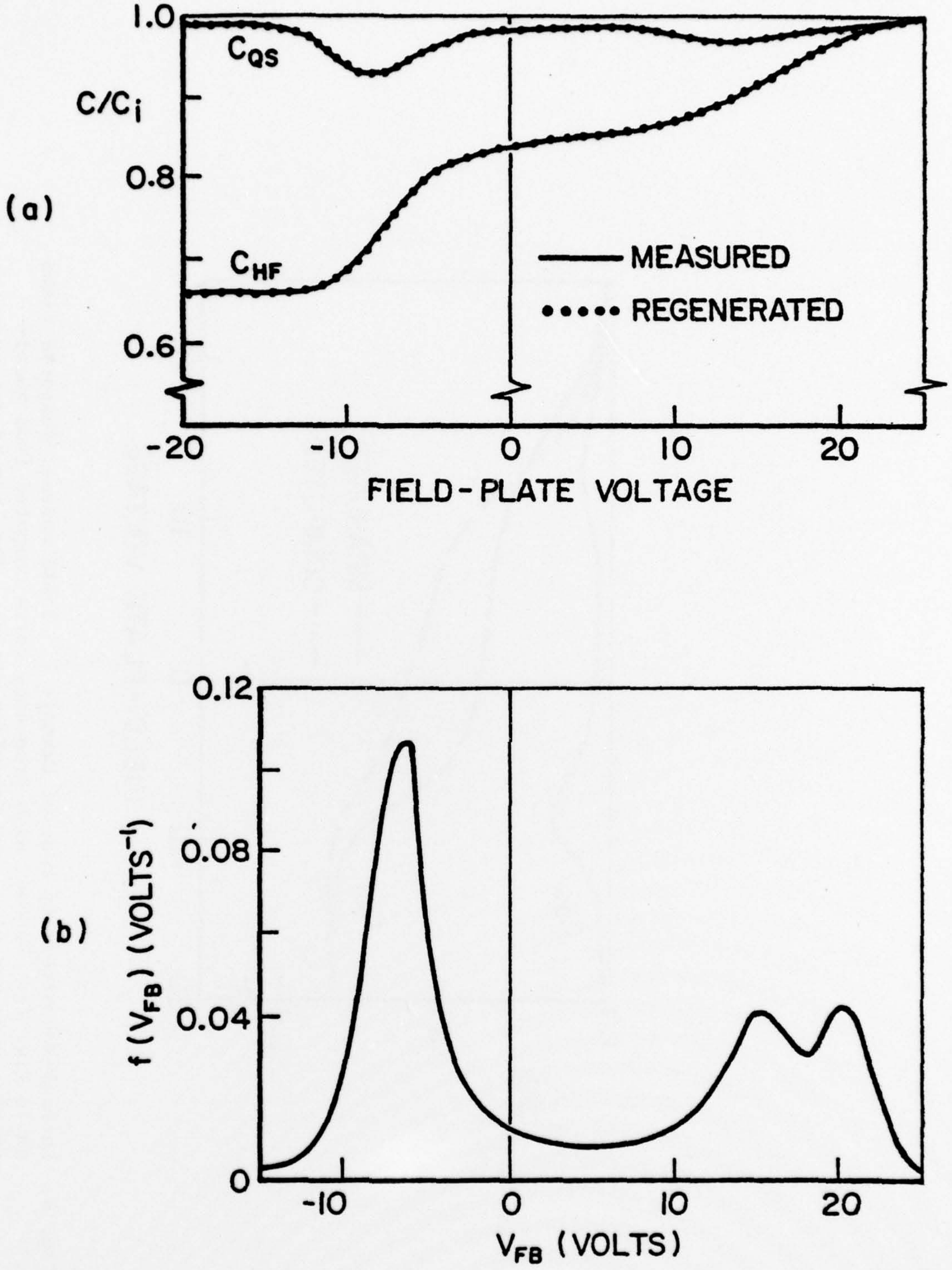

Fig. 7. Interface-state test of Example 2. (a) Solid curves: Measured after electron-beam bombardment. Dots: Regenerated curves computed from the flatband-voltage distribution shown in (b). The agreement in (a) indicates that interface states are not important.

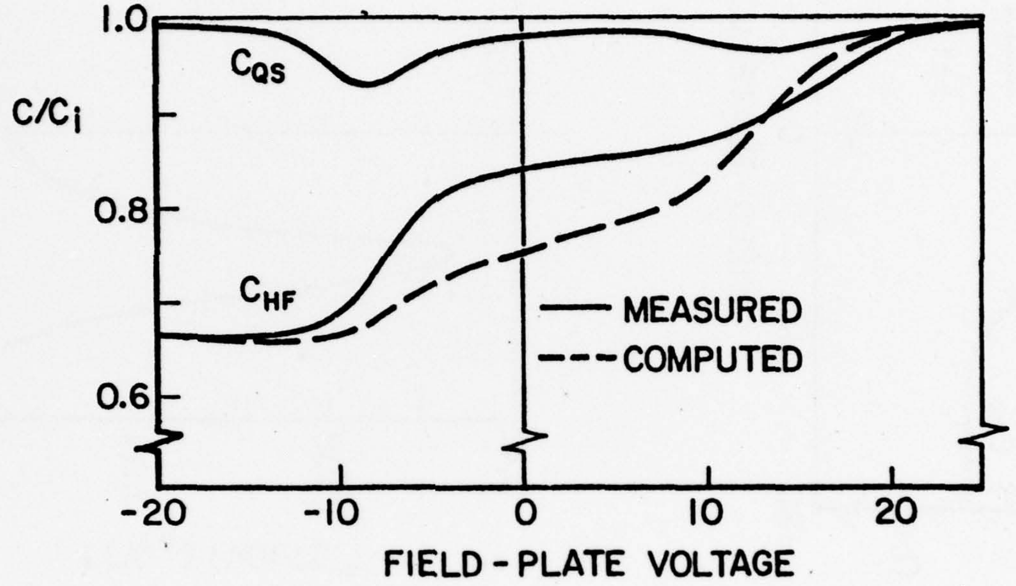

Fig. 8. Lateral-nonuniformity test of Example 2. Solid curves: Measured (same as in Fig. 7). Dashed: High-frequency curve computed from quasi-static curve assuming only interface states. The lack of agreement shows the presence of lateral nonuniformity.

voltages in an MIS capacitor with laterally nonuniform fixed charge in the insulator, and (2) a method which utilizes the concept of a distribution of flatband voltages to distinguish between interface states and laterally nonuniform fixed charge.

The method for determining the distribution of flatband voltages in an MIS capacitor with nonuniform charge storage is based on approximating the difference between the quasi-static and high-frequency capacitances of an ideal MIS capacitor by a step function. This results in the simple relations given by (2) and (3) for p-type and n-type substrates, respectively.

The proposed test for lateral nonuniformities makes use of a principle implicit in the results of an analysis made by Brews and Lopez [3]: If a C-V abnormality is caused by lateral nonuniformities (interface states), the resulting quasi-static and high-frequency curves cannot <u>both</u> be fitted by any distribution of interface states (flatband voltages). A method of making use of this principle is to test for each cause of C-V abnormality by assuming the other effect to be the true cause. If laterally nonuniform fixed charge is assumed, the method of Sec. II can be used to determine the distribution of flatband voltages, and the quasi-static and high-frequency C-V curves can be regenerated from this. If interface states are assumed, the quasi-static C-V curve can be used to compute the high-frequency curve. In either case, a mismatch will indicate the presence of the abnormality assumed not to be present.

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