Analysis of the temporal instability of the parameters of an insulator/III–V compound by the isothermal capacitance relaxation method

L. S. Berman

A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia
(Submitted December 14, 1995; accepted for publication March 12, 1996)

Existing diagnostic techniques used to evaluate the temporal instability of the parameters of a semiconductor–insulator interface with deep-level centers are analyzed. A method is proposed for evaluating temporal instability according to the long-term isothermal transient behavior of the capacitance of a metal–insulator–semiconductor structure. The energy spectrum of the effective density of surface states is determined for n-type InP–SiO 2 –Al structures prepared by chemical vapor deposition. The variation of the capacitance during long-term isothermal relaxation provides a criterion of temporal instability of a semiconductor–insulator interface. © 1997 American Institute of Physics. [S1063-7826(97)01601-3]

INTRODUCTION

The foremost unsolved problem in the physics of insulator/III–V compound interface structures is the temporal instability of the interface parameters.

A unified procedure for evaluating the temporal instability of the interface does not exist at present. Estimates based on the capacitance properties of a metal–insulator–semiconductor (MIS) are preferred over estimates based on the drift current of an MIS transistor, because the fabrication of an MIS structure requires fewer auxiliary technological operations affecting the interface parameters; moreover, the stability of an MIS structure does not depend on the carrier mobility. In a number of papers, therefore, it has been the practice to characterize the instability of the interface by the width of the hysteresis loop of the capacitance–voltage (C–V) characteristic de-

(A) Basic Equations

We specify long-term holding of the MIS structure at \( V = V_1 \) (Fig. 1a) for a time exceeding the subsequent time to measure the transient process by more than an order of magnitude. Surface states with energies \( E < F_n \) are filled with electrons, which tunnel from the surface states into the depth of the semiconductor with a time constant \( \tau_r \), which is determined from the approximate equation

\[
\tau_r = \alpha^{-1} \exp\left[ \frac{1}{2} \left( \frac{b \Phi}{e} \right)^{1/2} \right],
\]

where \( z \) is the tunneling depth (in angstroms), \( b \) is the ratio of the effective mass of an electron in the insulator to the free-electron mass, \( \Phi \) is the height of the potential barrier (in electron-volts), and \( \alpha \) is the preexponential factor, which depends on \( \Phi \) and \( z \) and on the parameters of the insulator (see Fig. 4 in Ref. 6).

During the holding period at \( V = V_1 \), the DL centers in the insulator with energies \( E < F_n \) are filled with electrons in the layer \( 0 < z_1 \).

The following relation holds at \( V = V_1 \):

\[
V_1 - V_{hi} = \Psi_{s1} - C_i^{-1} [Q_{ss1} + Q_{st1} + Q_{i1}],
\]

\( C_i \) is the isothermal capacitance relaxation method.

THEORY

(A) Statement of the Problem

The thickness of the insulator \( d \) exceeds a few hundred angstroms, and tunneling clear through the insulator can be disregarded. There is a fragmented layer with a thickness of the order of several tens of angstroms near the insulator–semiconductor interface and a fragmented layer near the metal–insulator interface. Upon integration of the Poisson equation the space charge density in the insulator is multiplied by the distance from the charge to the electrode on the insulator. Consequently, if the densities of DL centers in the two both layers are of the same order of magnitude, then the second layer exerts a much weaker influence than the first on the capacitance of the MIS structure. We shall consider only the first fragmented layer and ignore the influence of the second on the capacitance of the MIS structure. We assume that the DL centers in the fragmented layer of the insulator exchange charge carriers only with the surface of the semiconductor by tunneling but not by tunneling between DL centers. For definiteness the calculations are carried out for n-type semiconductors.

(B) Basic Equations

We specify long-term holding of the MIS structure at \( V = V_1 \) (Fig. 1a) for a time exceeding the subsequent time to measure the transient process by more than an order of magnitude. Surface states with energies \( E < F_n \) are filled with electrons, which tunnel from the surface states into the depth of the semiconductor with a time constant \( \tau_r \), which is determined from the approximate equation

\[
\tau_r = \alpha^{-1} \exp\left[ \frac{1}{2} \left( \frac{b \Phi}{e} \right)^{1/2} \right],
\]

where \( z \) is the tunneling depth (in angstroms), \( b \) is the ratio of the effective mass of an electron in the insulator to the free-electron mass, \( \Phi \) is the height of the potential barrier (in electron-volts), and \( \alpha \) is the preexponential factor, which depends on \( \Phi \) and \( z \) and on the parameters of the insulator (see Fig. 4 in Ref. 6).

During the holding period at \( V = V_1 \), the DL centers in the insulator with energies \( E < F_n \) are filled with electrons in the layer \( 0 < z_1 \).

The following relation holds at \( V = V_1 \):

\[
V_1 - V_{hi} = \Psi_{s1} - C_i^{-1} [Q_{ss1} + Q_{st1} + Q_{i1}],
\]

\( C_i \) is the
where \( V_1 - V_{bi} \) is the difference between the work functions of the metal and the semiconductor, \( q \) is the electron charge, \( \Psi_{s1} \) is the surface potential, \( C_i \) is the capacitance of the insulator, \( Q_{sc1} \) is the charge in the space charge region of the semiconductor, \( Q_{ss1} \) is the charge of the surface states and DL centers in the \( \delta \) layer of the insulator, \( Q_{eff} \) is the effective (averaged) charge in the insulator, determined from the expression

\[
Q_{eff} = (d - \delta)^{-1} \int_0^{d-\delta} \rho(x) dx, \tag{3}
\]

\( \delta \) is the thickness of the layer (of the order of several tens of angstroms) in which charge carriers are exchanged between the insulator and the semiconductor during the measurement, \( \rho \) is the space charge density, and the coordinate \( x \) is measured from the metal (the capacitances and charges are given per unit area).

At \( t = 0 \), we switch the structure from \( V_1 \) to \( V_2 \) (from enrichment to depletion; see Fig. 1). Switching is followed by the thermionic emission of electrons from surface states into the conduction band with a time constant \( \tau_{th} \), which is determined from standard relations.\(^9,10\) After thermionic emission from surface states with energies \( E > E(\xi) \) electrons tunnel their way to these surface states from DL centers in the insulator with a time constant \( \tau_T \), determined from (1); the electrons then experience thermionic emission from the surface states into the conduction band. The layer from which the electrons arrive is marked with horizontal striations in Fig. 1b.

The following relation holds at \( V = V_2 \):

\[
V_2 - V_{bi} = \Psi_{s2} - C_i^{-1}[Q_{sc2} + Q_{s1} + \Delta Q_{ss2} + Q_{eff}], \tag{4}
\]

where \( \Delta Q_{ss} \) is the charge variation of the surface states and DL centers in the \( \delta \) layer after switching; from now on we regard these two interacting charges as a single charge of DL centers with a number density \( N_d \); \( \Delta Q_{eff} \) is the charge variation in the insulator in strong fields (avalanche injection or the Fowler–Nordheim effect). The rest of the notation has the same significance as in (2), and the subscript 2 corresponds to \( V = V_2 \).

After \( \Psi_{s2} \) is increased (diminishing band bending) to a certain value \( \Psi_{s2}^* \), the charge \( \Delta Q_{eff} \) does not change. We assume that after switching from \( V_1 \) to \( V_2 \) the inequality \( \Psi_{s2}^* - \Psi_{s2}^* \) holds during the entire transient process, so that \( \Delta Q_{eff} \) can be disregarded.

(C) Solution

Subtracting Eq. (4) from (2), we obtain

\[
V_1 - V_2 = \Psi_{s1} - \Psi_{s2} - C_i^{-1}[Q_{sc1} - Q_{sc2} - \Delta Q_{ss}]. \tag{5}
\]

a) We specify \( V_1 \) in such a way as to satisfy the inequality \( C_{sc1} \gg C_{s1} \), where \( C_{sc1} \) and \( C_{s1} \) are the capacitance of the space charge region and the capacitance of the surface states, respectively; at \( V = V_1 \), this inequality can be satisfied in the enrichment mode. We then have

\[
C_{sc1} = [C(V_1)^{-1} - C_i^{-1}]^{-1}, \tag{6}
\]

where \( C(V_1) \) is the capacitance of the MIS structure at \( V = V_1 \). The capacitance \( C_{sc1} \) can be calculated from (6) using the known values of \( C(V_1) \) and \( C_i \). Since \( C_{sc} \) and \( Q_{ss} \) are known functions of \( \Psi_\xi \) (Refs. 9 and 10), \( \Psi_{s1} \) and \( Q_{sc1} \) can be calculated from the known value of \( C_{sc1} \).

b) We specify \( V_1 \) in such a way as to satisfy the inequality \( \Psi_{s1} \leq \Psi_{sc} \), where \( \Psi_{sc} \) is determined from the condition

\[
2 \pi f \tau_{th}(\Psi_{sc}) = 1, \tag{7}
\]

in which \( \tau_{th}(\Psi_{sc}) \) is the time of thermionic emission from the level \( E = E_n \) when \( \Psi = \Psi_{sc} \); in other words, the rf capacitance is measured at \( V = V_1 \) (see also Ref. 11). Now \( C_{sc1}, Q_{sc1}, \) and \( \Psi_{s1} \) can be calculated as in case a).

Let us assume that the inequality \( \Psi_{s2} \leq \Psi_{sc} \) holds after switching. We also assume that the MIS structure stays in the depletion mode (without forming an inversion layer). At \( V = V_2 \) the values of \( C_{sc2}, Q_{sc2}, \) and \( \Psi_{s2} \) can then be calculated as for \( V = V_1 \), i.e., from the experimental values of the measured capacitance. Consequently, \( \Delta Q_{ss}(t) \) can be determined from (5).

We now examine limiting cases.

a) The inequality \( \tau \tau_{th} \leq \tau_{th} \) is satisfied for \( \delta \) of the order of a few angstroms. Methods for determining the energy spectrum of the surface states \( N_{ss}(E) \) in this case have been developed in detail.\(^9,10,12\)