Experimental observation of conductance transients in Al/SiN$_x$:H/Si metal-insulator-semiconductor structures

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Room temperature conductance transients in the SiN$_x$:H/Si interface are reported. Silicon nitride thin films were directly deposited on silicon by the low temperature electron-cyclotron-resonance plasma method. The shape of the conductance transients varies with the frequency at which they are obtained. This behavior is explained in terms of a disorder-induced gap-state continuum model for the interfacial defects. A perfect agreement between experiment and theory is obtained proving the validity of the model. © *1997 American Institute of Physics.* [S0003-6951(97)03732-7]

Presently, ultrathin silicon dioxide gates (30–40 Å) are required as a consequence of the reduction in the ultralarge-scale-integration (ULSI) silicon device dimensions. On the other hand, silicon nitride, Si_3N_4, has been successfully used as an insulator with different III-V semiconductors. Two important properties of silicon nitride (Si_3N_4) make it a candidate to substitute silicon dioxide, SiO_2, in ultrathin dielectric structures: silicon nitride has a higher dielectric constant and exhibits a better performance as a diffusion barrier than silicon dioxide. Nevertheless, the interface between Si_3N_4 and Si is not as well known as the SiO_2/Si interface and significantly higher densities of interfacial states are always displayed by the silicon nitride/silicon structure.

In this letter we report for the first time the existence of conductance transients in Al/Si_3N_4/Si structures. As we show later, this behavior is related to the existence of a spatial distribution of interface states. We use metal-insulator-semiconductor (MIS) diodes in which a 550-Å-thick SiN$_x$:H film was directly deposited on ⟨100⟩ n-type silicon by electron-cyclotron-resonance (ECR) plasma at 200 °C. Silicon nitride films have been fabricated with a wide composition range[1] from Si-rich to near stoichiometric and N-rich films. For compositions far from the stoichiometry the hydrogen content increases and the number of electrically active defects in the film increases due to the distortion in bonds induced by hydrogen,[2] in spite of the dangling bond saturation that it produces. In a previous work[3] we have proved by capacitance-voltage (C-V) and deep-level transient spectroscopy (DLTS) studies that the electrical properties of these films are closely related to hydrogen content. We observed hysteresis phenomena in the C-V curves. This behavior has been previously reported by Lau *et al.*[4] and may be understood by the defect model suggested by Hasegawa *et al.*[5,6] These authors proposed that the interface states are distributed both in energy and in space. This distribution is called disorder-induced gap-state (DIGS) continuum. Emission and capture of free electrons by states located far from the interface can occur by mean of tunneling mechanisms.[7] When bias varies from inversion to accumulation, electrons in the semiconductor conduction band are captured by emptied interface states, whereas when moving in the opposite direction electrons are emitted from filled interface states to the conduction band of the semiconductor. Since these processes are tunneling assisted, they are slow and nonsymmetrical. That causes the experimental capacitance values to depend both on the direction and on the speed of the voltage variation and, therefore, hysteresis effects are observed.

Room temperature conductance transients are obtained when we apply positive pulses in the bias that drive MIS structures from deep to weak inversion. Subsequently, capture processes take place in which the empty DIGS states trap electrons coming from the conduction band. This process is assisted by tunneling and is time consuming. States near the interface capture electrons before those located farther away in the dielectric bulk. In Figure 1 we show several conductance transients at three frequencies. The most noticeable point is that the transient shape varies significantly with the frequency. For the lowest frequency, the conductance remains constant at the beginning of the transient and it increases at times longer than about 1 s. Conversely, at high

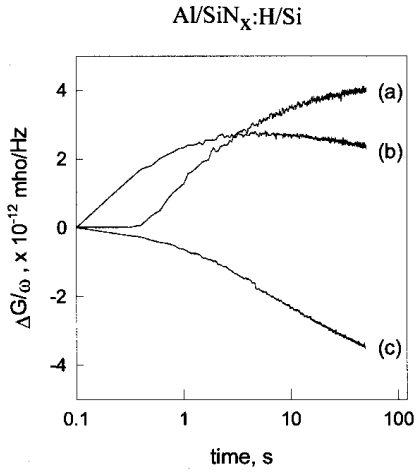

FIG. 1. Room temperature conductance transients of Al/SiN$_x$:H/Si structures at several frequencies: (a) 37 Hz, (b) 71 Hz, and (c) 123 Hz.

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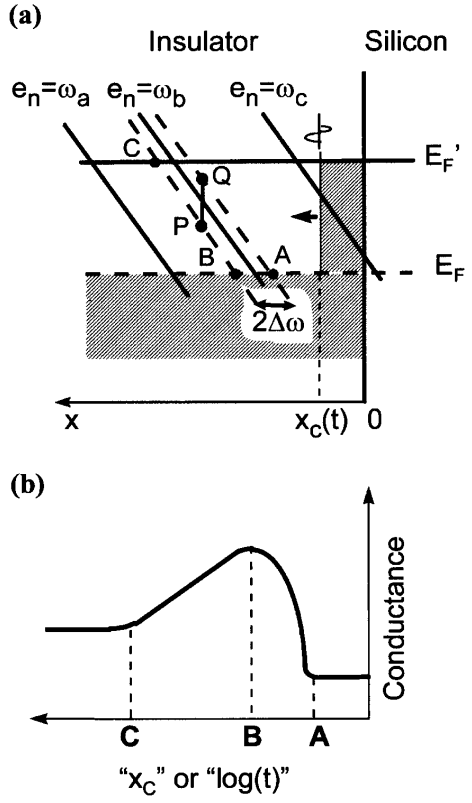

FIG. 2. (a) Schematic band diagram of an I-S interface illustrating the capture of electrons by DIGS continuum states during a conductance transient. (b) General shape of the conductance transient.

frequency we obtained decreasing transients. At intermediate values the transients have a mixed behavior: first they increase, then reach a maximum value and, after that, they decrease towards a stationary value.

Conductance transients can be explained in terms of the spatial distribution of the interface states.[8] When the states are spatially distributed the electron emission and capture processes involve both thermal excitation and tunneling. In Figure 2(a) we show a schematic of the insulator-semiconductor (IS) structure during a transient. E_F and E_F' are the relative locations of the Fermi level with respect to the interface states before and after the pulse. In this plot we also draw lines corresponding to the states having the same electron emission rate.[9] The point $x_c(t)$ is the distance covered by the front of tunneling electrons during the time t. This distance is given[6,7] by

$$x_{cn}(t)=x_{on}\,\ln(\sigma_{on}v_{thn}n_s t)\,, \tag{1}$$

where $x_{on}=h/4\pi(2m_{eff}H_{eff})^{1/2}$ is the tunneling decay length, σ_{on} is the electron capture cross section value for x=0, v_{thn} is the electron thermal velocity, and n_s is the free electron density at the interface. In order to make estimate $x_{\mathrm{cn}}(t)$ we used the following values of the different parameters: DiMaria and Arnett[10] reported a height of 1.9 eV for the silicon-nitride/silicon energy barrier, H_{eff}. That gives a value of 1.25 Å for x_{on}. Empirical data for σ_{on} are typically in the range $0.5–5\times10^{-14}$ cm^2. Assuming weak inversion conditions ($n_s\approx10^{17}$ cm^{-3}) we conclude that the front of tunneling electrons reaches depths of 28.8, 31.7, and 34.3 Å after times of 1, 10, and 100 s, respectively.

It is well known that only those traps with emission and capture rates of the same order of magnitude than the frequency have non-zero contributions to the conductance.[11] Let us assume in Figure 2(a) an experimental frequency ω_b and that only those states with emission rates in the range $\omega_b\pm\Delta\omega$ have non-negligible contribution to the conductance. At the beginning of the transient the front of tunneling electrons is very close to the interface. Therefore, all the states capturing electrons have emission rates very much higher than the frequency and do not produce any change in the conductance of the structure. When $x_c(t)$ reaches the point A, the states with emission rate equal to ω_b and with energy slightly higher than E_F give some contribution to the conductance signal. After that, more and more states are subsequently incorporated. When $x_c(t)$ reaches the point B the range $\omega_b\pm\Delta\omega$ is completed. In summary, the conductance signal increases during the time employed in going from A to B. From then, the states contributing to the conductance at a time t' are those indicated by the segment PQ. This segment moves from B to C following the equi-emission lines and the instantaneous conductance is proportional to the density of states in this segment. Once $x_c(t)$ reaches point C the states with emission rates in the measurable range now have energies above the Fermi level, E_F', and remain empty. Afterwards, no contribution of the interfacial states can be measured and the conductance reaches a stationary value. As the profile of states usually decreases with x, the shape of the conductance transient is like that plotted in Figure 2(b). For the frequency ω_c, the initial situation corresponds to some point between B and C and the observed transient will follow the interface states profile. Finally, the transient corresponding to the frequency ω_a is similar to that for ω_b but with an additional delay. This model explains our experimental transients of Figure 1. Curves (b) and (c) correspond to the cases of ω_b and ω_c in Figure 2(a). In the case of the lowest frequency (37 Hz) the transient is ever increasing. The 50 s record seems not to be long enough to complete the measurable emission rate range for this frequency due to the fact that the time needed by electrons to reach deeper positions in the insulator exponentially increases with the distance.

In addition, we have made measurements keeping constant the frequency and varying the temperature. We have detected conductance transients at temperatures as low as 200 K. This fact supports the assumption of tunneling assisted (i.e., temperature independent) capture process. Besides, as the temperature decreases the transients are modified in a similar way as when frequency is increased at constant temperature: the lower the temperature is, the faster the transients become. That is easily explained taking into account the fact that the emission rate is a function of the temperature: as temperature decreases the emission rates of all interface states exponentially decrease and the equi-emission lines shift approaching the interface and shorter distances have to be covered by the front of tunneling electrons.

In conclusion, the anomalous conductance transients observed in the Si_3N_4/Si interface are very well explained with the model of a spatial distribution of interface states and confirm the assumptions of this model. Moreover, we show

that the shape of these transients is closely related to the spatial and energetic distribution of the interface states. We are presently increasing our efforts to obtain a precise formulation for these transients allowing one to derive the spatial and energetic distribution of interface states from the experimental measurements.

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