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Electronic properties of Al-SiO₂-(n or p) Si MIS tunnel diodes (+)

J. Vuillod and G. Pananakakis

LPCS (UA-CNRS 840), INPG-ENSERG, 23, av. des Martyrs, 38031 Grenoble Cedex, France

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Résumé. — Des mesures automatiques I - V , $C/G(V, \omega)$ sont utilisées pour étudier les propriétés électriques d'un grand nombre de diodes MIS tunnel Al-SiO₂-(n ou p) Si avec une épaisseur d'oxyde de 30 Å fabriquées selon les procédés LPO₂ et LPCVD. Une comparaison entre les caractéristiques I - V et C - V de dispositifs sur substrats n et p est effectuée ainsi qu'une étude de dispersion des caractéristiques I - V . La modélisation des caractéristiques I - V a été effectuée grâce à un modèle de simulation avec deux niveaux d'états d'interface. La variation des principaux paramètres de la modélisation est corrélée avec la variation des caractéristiques I - V due à la dispersion. Les densités d'états d'interface déduites de la modélisation sont en bon accord avec les valeurs obtenues à partir des mesures $C/G(V, \omega)$.

Abstract. — Automatic measurements I - V , $C/G(V, \omega)$ are used to study the electrical properties of a great number of aluminum-SiO₂-n or p type silicon MIS tunnel diodes with an oxide thickness of 30 Å prepared by two technologies of oxidation, low pressure chemical vapour deposition (LPCVD) and low oxygen pressure (LPO₂). A comparison between the I - V and C - V characteristics on n and p substrate is presented as well as a dispersion study of I - V characteristics. The modelling of I - V characteristics has been carried out with a simulation model with two single level interface states. The variation of the main parameters of the modelling is connected with the variation of I - V curves provoked by the dispersion. The interface state densities deduced of the modelling are in agreement with those obtained from the $C/G(V, \omega)$ measurements.

Notation.

C_m	measured parallel capacitance	R_s	series-resistance
C_p	(parallel) sum of space charge capacitance and interface state capacitance	V_a	applied d.c. bias
C'_p	parallel interface state capacitance	V_s	surface potential in silicon
C_{ox}	oxide capacitance	V_{s0}	surface potential in silicon at zero bias
C_{sc}	silicon space charge capacitance	δ	oxide thickness
E_T	energy of interface states in silicon band-gap	Φ_B	barrier height of metal-semiconductor barrier
f	signal frequency	χ_n, χ_p	effective electron, hole affinities
G_m	measured parallel conductance	ω	angular frequency
G_p	parallel interface state conductance		
G_T	tunnelling conductance		
I	current		
J	total current density		
n	ideality factor		
N_A, N_D	acceptor, donor densities in silicon		
N_{s0}	interface state densities of acceptor level located at E_{T0} below the conduction band		
N_{s1}	interface state densities of donor level located at E_{T1} below the conduction band		
N_{ss}	interface state density		

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1. Introduction.

There is a practical interest in the study of conducting Metal-(Ultra-thin SiO₂) Insulating-(Si) Semiconductor structures generally called MIS tunnel diodes because of their uses in microelectronics (VLSI, memory devices, photodiodes arrays) and in photo-cells applications.

There is also a fundamental interest in these studies because these very thin silicon oxide layers (30 Å here) on silicon represent the initial stage of silicon oxidation.

In this paper current-voltage characteristics on n and p type silicon substrate are presented as well as capacitance and conductance characteristics.

Using a self consistent numerical model of the working of MIS tunnel diodes developed by the authors [1, 2] the dispersion of the current-voltage characteristics of diodes on the same wafer are studied and analysed.

This work based on fully automatic experimental apparatus controlled by microcomputers, allows us to deduce extreme dispersion values of the most important physical parameters at the Si-SiO₂ interface : electronic affinity, oxide thickness, density and energy location of interface states.

Besides comparison between current-voltage and capacitance, conductance-voltage characteristics permits to complete and confirm the previous results.

2. Technological characteristics of the samples.

The devices have been fabricated in EFCIS/Thomson laboratories on $\langle 100 \rangle$ oriented n type and p type silicon substrate (N_D or $N_A = 10^{15} \text{ cm}^{-3}$) by two technological processes described elsewhere [1] to obtain oxide films of 30 Å thickness, measured by ellipsometry :

— Thermal oxidation under low oxygen pressure at 950 °C called LPO₂.

— Low pressure chemical vapour deposition of SiO₂ at 880 °C called LPCVD.

Eight kinds of structures have been studied : LPCVD and LPO₂ oxides on n and p type substrate without and with thermal annealing at 400 °C during 30 min under N₂ atmosphere. A great number of tunnel diodes have been tested (the total number of devices tested is about 50) by using evaporated aluminum electrodes typically of 400 μm × 400 μm on the top surface, wires are attached by ultrasonic bonding on these metallizations. Back contacts are gold or silver. No one measurement has been carried out by pressure and point contact. A special mask is used to permit the realization of the connections, which are made on thick oxide layer parts (Fig. 1).

3. Apparatus of measurement.

In this work automatic data acquisition is always performed. It permits the study of a great number of devices quickly, the storage of data on floppy disks for further treatments and calculations. The following measurement apparatus have been used :

- $I(V)$ measurement unit (automatic HP4140B pA meter-DC voltage source) connected through the IEEE bus-line cable to a HP9826 computer and a HP2673A graphics printer.

- $C(V)$, $G(V)$ measurement unit described elsewhere [3] including principally :

an automatic Brookdeal lock-in amplifier with an IEEE interface connected to an Apple II computer, a preamplifier, a Boonton precision decade capacitor and a HP plotter.

- Automatic semiconductor component test sys-

Fig. 1. — Schematic of the elementary pattern of the metallic engraving.

tem (HP4061A) consisting of a 4275A multifrequency LCR meter for AC impedance measurements from 10 kHz to 10 MHz, a 4140A pA meter-DC voltage source, a switching subsystem, a 9826A controller and a 7470A plotter. This system permits among others : $I-V$, $C-V$ quasi-static, doping profile measurement and gives bias and/or frequency characteristics of devices.

4. Current voltage characteristics.

Typical current-voltage $I-V_a$ and current density voltage $J-V_a$ characteristics in linear and semilogarithmic plots are shown respectively in figure 2 for the eight kinds of MIS tunnel diodes mentioned in section 2. All measurements are made in the dark.

4.1 CHARACTERISTICS ON n TYPE SUBSTRATE. — Typical characteristics are represented in linear (range of 10^{-8} or 10^{-9} A) and semilogarithmic plots in figures 2a and b respectively. The reverse curves present a saturation current, the density is of the order of 10^{-4} to 10^{-2} mA/cm^2 (Fig. 2b).

The reverse characteristics show sometimes a « threshold effect » particularly for devices without annealing (curve 2 in Fig. 2a) : the current is first very low and then remains constant for bias lower than -0.3 V . The authors have explained this effect in a previous paper by introducing electrostatically acting donor-like interface states in the vicinity or below of the semiconductor midgap [1]. For the forward characteristics it may be observed that an exponential law is not generally obtained, the characteristics in semilog plot are curved towards the voltage axis. Sometimes other shapes may be observed (curve 1 in Fig. 2b), first the characteristics are slightly curved towards the voltage axis and then above 0.3 V the current increase more rapidly.

It may be noted also that there is a tendency to obtain larger ideality factors for non annealed samples (curves 2 and 2' in Fig. 2b).

The figure 3 shows the dispersion of $J-V_a$ characteristics of devices obtained on the same wafer in the

Fig. 2. — Experimental current-voltage characteristics for LPCVD (solid lines) and LPO₂ (dashed lines) Al-SiO₂-Si diodes on n (a and b) and p type wafer (c and d) annealed (curves 1) or not (curves 2). For n type devices $V_a = V_m - V_{sc}$ whereas for p type devices $V_a = V_{sc} - V_m$, so that the curves have familiar shapes for both n and p type wafer (V_m , V_{sc} bias to metal and to semiconductor respectively).

Fig. 3. — Experimentally observed dispersion of J - V_a characteristics for LPCVD (solid lines) and LPO₂ (dashed lines) annealed or not devices on n (a and b) and p (c and d) type wafer ((A)SiO₂ : annealed SiO₂, (NA)SiO₂ : not annealed SiO₂).

case of annealed or not samples. The shapes of the curves are preserved (saturation effect for reverse bias, characteristics generally curved toward the voltage axis for forward bias). There are approximately two orders of magnitude of dispersion in the reverse characteristics at -0.7 V. The experimental dispersion of the $J(V)$ characteristics depends on the parameters mentioned in section 4.3.2 and mainly of δ , χ (the tunnelling current is proportional to $\exp(-\chi^{0.5}\delta)$) and the density of the states.

Hysteresis on current-voltage characteristics has been studied. The 4140B pA-meter mentioned in section 3 has a voltage source with a double staircase wave : output voltage changes step by step from start voltage to stop voltage. Successively, output voltage is returned to start voltage by same step voltage. The hold time at beginning and end of voltage ramp is fixed to 1 s. The annealed LPCVD oxides on n type substrate do not show hysteresis. Generally for a step delay time of 10 s and 1 s there is no observable hysteresis. Slight displacements between the curve corresponding to an increasing voltage (from start to stop voltage) and the curve corresponding to a decreasing voltage are observed for short delay times 0.1 s and particularly 0.01 s. This is due to time response of the circuit.

4.2 CHARACTERISTICS ON p TYPE SUBSTRATE. — Typical characteristics are represented in linear (range of 10^{-10} A) and semilogarithmic plots in figures 2c and d respectively. The reverse characteristics have a tendency to present a saturation effect around a voltage of -1 V (Fig. 2d), the density of current is in the range of 10^{-5} mA/cm².

Some forward characteristics exhibit a kind of plateau similar to that presented by Shewchun *et al.* [4] the current increases approximately exponentially with voltage for low voltage values then increases less rapidly, and at last starts to increase rapidly with voltage above 0.6 V (curve 1 in Fig. 2d). These authors [4, 5] explained this kind of plateau by considering the distribution of the external applied voltage between the oxide layer and the semiconductor, when the semiconductor surface goes from depletion to accumulation regime. This plateau effect is attenuated by the action of interface states.

The dispersion curves are shown in figures 3c and d. The reverse characteristics show a saturation effect, we have approximately a dispersion of two orders of magnitude, the forward characteristics show often the kind of plateau mentioned above (curves 1 in Figs. 3c and d).

Hysteresis on current-voltage characteristics has been studied. As in n type device slight displacements between the curve corresponding to an increasing voltage and the curve corresponding to a decreasing voltage are observed for short delay times of 0.1 s or 0.01 s (see section 4.1). No hysteresis is observable for delay times above 1 s.

4.3 DISCUSSION.

4.3.1 Comparison of MIS tunnel diodes on n and p type substrate. — As a general rule, there is at least an order of magnitude between the currents (forward or reverse) for the same bias range in MIS tunnel diodes on n and p type wafers (see Fig. 1). There are also some differences in the shape of the forward curves, the effect of « plateau » mentioned in section 4.2 appears only in devices on p type substrate significantly. We can note also that there is no important difference between the I - V characteristics for the devices prepared by LPO₂ and LPCVD technologies (see section 4.1).

It is known in the literature [4-7] that majority carriers dominate the tunnel current in tunnel diodes on n type substrate and that minority carriers dominate in Al-SiO₂-pSi structures. Indeed the Al-SiO₂-pSi structure has naturally a large metal-semiconductor barrier height Φ_B as a result of the difference in work function between Al and p type Si. This can explain the difference in the magnitude of currents in n and p type structure. The results on capacitance-voltage measurements presented further corroborate this analysis, we see indeed that the silicon surface is inverted for zero bias for p type structure and near accumulation for n type.

We have quoted above, papers giving a detailed numerical and experimental analysis of MIS tunnel diodes on p wafer [4, 5]. In the present work we use a simulation model [1, 8] developed for an n type semiconductor, particularly to study the dispersion of I - V characteristics on n type silicon. The results obtained using this model are presented in the next section (4.3.2).

4.3.2 Modelling study connected to the dispersion of I - V curves. — In MIS tunnel structures with a very thin oxide layer the mechanisms for current conduction are : tunnelling between the metal and the majority carrier energy band in the semiconductor, tunnelling between the minority carrier energy band, tunnelling between the metal and surface state levels (surface states act as recombination generation centres and provide additional tunnelling paths between the metal and the semiconductor). From these considerations, a simulation model for the working of MIS tunnel structures has been developed by the authors [1, 8]. In this model the usual differential equations describing the potential distribution and the transport of free carriers are replaced by a nonlinear algebraic equation system : the numerical solution becomes easier and it needs shorter computation time. The modelling is carried out on Multics CII-HB67 computer. The actual continuous distribution obtained by $C/G(V, \omega)$ studies is replaced by discrete levels (here two), in order to simplify the simulation program and decrease the calculation time.

a) An acceptor-like level located near conduction band ($E_c - E_{T_0}$ typical value 0.3 eV) having a density N_{s_0} and an electrostatic and kinetic action [2], acting

essentially on the forward characteristics and less on the reverse characteristics.

b) A donor-like level E_{T_1} located typically at the vicinity of the midgap having a density N_{s_1} and an electrostatic action [2], acting on the reverse characteristics and allowing us to simulate the threshold effect observed on the reverse characteristics.

The other important parameters of the modelling which enable to fit the experimental and theoretical curves are : the oxide thickness δ and the effective electron/hole affinities χ_n, χ_p .

It is not necessary to introduce a fixed charge in the numerical simulation. Indeed the interface state densities used, allow us to fit the experimental results and are consistent with the values obtained by experimental measurements ($C/G(V, \omega)$).

Typical modelling curves are shown in figures 4a and 4b for LPCVD and LPO₂ devices respectively. We note that a satisfactory modelling can be found with only two single levels of interface states by simply varying the values of $\delta, \chi_n, E_{T_0}, E_{T_1}, N_{s_0}, N_{s_1}$. We can remark (Figs. 4a and b) that the observed discrepancies between experimental and theoretical curves are due to the fact that our calculations are based on single level interface states which actually replace the continuous distribution.

We can discuss now the variation of modelling parameters. For example between the curves (1') and (3') of figure 4a we have a variation of J of two orders of magnitude (for $V_a = -1$ V). By supposing that there is no dispersion of the typical oxide thickness value ($\delta = 30$ Å), we find using our model a χ_n variation of 0.15 eV, a N_{s_0}, N_{s_1} variation of $9 \times 10^{11} \text{ cm}^{-2}$ and $2.4 \times 10^{11} \text{ cm}^{-2}$ respectively.

Between the curves (1') and (3') of figure 4b we find in the conditions mentioned above a variation for χ_n of 0.18 eV, for N_{s_1} of $1.8 \times 10^{11} \text{ cm}^{-2}$ and no variation of N_{s_0} . In conclusion with the assumption of constant oxide thickness, we can modelize experimental extreme curves of figure 4 with a variation of χ_n lower than 0.2 eV and a variation of interface state density (N_{s_0} or N_{s_1}) lower than $9 \times 10^{11} \text{ cm}^{-2}$. It may be noted that the variation of the current obtained by the simulation model are very sensitive particularly to the variations of χ and also to the variations of the state density of donor type (N_{s_1}) acting on the reverse characteristics (see above). The acceptor states (N_{s_0}) acting on the forward characteristics play a less important role due to their energetical position with regard to the Fermi level. The accuracy is then not as good for the acceptor states (N_{s_0}) than for the donor states (N_{s_1}). The χ values determined by the modelization are consistent with those reported in the literature [9]. To our knowledge the physical reasons of the observed dispersion of χ values has not been studied in the literature.

On the contrary if we assume a possible thickness dispersion in the order of 2 Å we can determine the values of the other parameters. Such thickness varia-

Fig. 4. — Fitting between experimental (solid lines) and theoretical (dashed lines) J - V_a curves for LPCVD (a) and LPO₂ (b) devices on n type substrate. Parameter of the modelling : $\Phi_{ms} = -0.15$ eV, $C_n = C_p = 2.5 \times 10^{-11} \text{ m}^3 \text{ s}^{-1}$, $\delta = 30$ Å. Other parameters (E_{T_0}, E_{T_1}, χ in eV, $N_{s_0}, N_{s_1} \text{ cm}^{-2}$, V_{s_0} in mV) :

Fig. 4a curve 1' $E_{T_0} = 0.3, E_{T_1} = 0.5, \chi = 0.80$
 $N_{s_0} = 10^{12}, N_{s_1} = 3 \times 10^{11}, V_{s_0} = 113$
 curve 2' $E_{T_0} = 0.3, E_{T_1} = 0.5, \chi = 0.80$
 $N_{s_0} = 10^{12}, N_{s_1} = 6 \times 10^{10}, V_{s_0} = 23$
 curve 3' $E_{T_0} = 0.3, E_{T_1} = 0.5, \chi = 0.95$
 $N_{s_0} = 10^{11}, N_{s_1} = 6 \times 10^{10}, V_{s_0} = 113$

Fig. 4b curve 1' $E_{T_0} = 0.25, E_{T_1} = 0.45, \chi = 0.82$
 $N_{s_0} = 5 \times 10^{11}, N_{s_1} = 2.6 \times 10^{11}, V_{s_0} = 77$
 curve 2' $E_{T_0} = 0.25, E_{T_1} = 0.5, \chi = 1.0$
 $N_{s_0} = 5 \times 10^{11}, N_{s_1} = 8 \times 10^{10}, V_{s_0} = 77$
 curve 3' $E_{T_0} = 0.25, E_{T_1} = 0.5, \chi = 1.0$
 $N_{s_0} = 5 \times 10^{11}, N_{s_1} = 8 \times 10^{10}, V_{s_0} = 77$

tion could corresponds to the insulating layer inhomogeneities on the wafer. These calculations were carried out using as an example the curve 1 of the figure 4a.

We find so :

— For $\delta = 30 \text{ \AA}$

$$N_{s0} = 10^{12} \text{ cm}^{-2} \quad N_{s1} = 3 \times 10^{11} \text{ cm}^{-2} \quad V_{s0} = 113 \text{ mV}$$

— For $\delta = 28 \text{ \AA}$

$$N_{s0} = 10^{12} \text{ cm}^{-2} \quad N_{s1} = 5 \times 10^{11} \text{ cm}^{-2} \quad V_{s0} = 32 \text{ mV}$$

Among these above two possibilities we can choose the first one which gives the V_{s0} value in accordance with the capacitance measurement for this sample (section 5). So with this reasoning the fluctuations of the thickness are not involved.

5. Capacitance and conductance-voltage characteristics.

5.1 EXPERIMENTAL RESULTS ON C AND G - V vs. BIAS AT DIFFERENT FREQUENCIES. — The curves of figure 5 (solid lines) present the variations of capacitance vs. bias for devices on n and p type wafers at several frequencies of measurement (C_m in linear scale).

Fig. 5. — Measured capacitance (solid lines) and conductance (dashed lines) versus applied voltage characteristics for devices on n(a) and p(b) wafer (linear plot for C_m and G_m).

For devices on n type substrate (curves 5a) we observe, in accumulation, plateau values C_{ma} , which correspond to the C_{ox} value (in the order of 1 900 pF) only at low frequencies (here 30 Hz). For higher frequencies the contact resistance R_s of the samples provokes a decrease of the C_{ma} values [10] (see equivalent circuits of Figs. 7a and b) :

$$C_{ma} = \frac{C_{ox}}{1 + R_s^2 C_{ox}^2 \omega^2} \left(\text{valid if } \frac{1}{R_s} \gg G_T \right).$$

This relation permits to evaluate R_s . We found R_s around 250 Ω .

For devices on p type substrate the accumulation is obtained for larger voltage value than in the case of n type device (Fig. 5b). It is obtained in accumulation region plateau values of C_{ma} lightly increasing with bias V_a . The series-resistance is found to be around 400 Ω in this case.

Fig. 6. — Measured capacitance (solid lines) and conductance (dashed lines) versus applied voltage characteristics for devices on n(a) and p(b) wafer (logarithmic plot for C_m and G_m).

Fig. 7. — Equivalent circuit of MIS tunnel diodes for series-resistance determination in accumulation (a and b) and for N_{ss} determination (c and d).

Accumulation begins at around -1 V in p type devices and 0.1 V in n type. These results are in agreement with the semiconductor surface regime at 0 voltage bias : inversion for p type devices and depletion-accumulation for n type devices (see section 4.3.1).

The curves of figure 5 (dashed lines) present the variations of the conductance vs. bias voltage with G_m in linear scale for the same devices as previously. The losses increase with the frequency [11] according to :

$$G_{ma} = \frac{G_T + R_s C_{ox}^2 \omega^2}{1 + R_s^2 C_{ox}^2 \omega^2} \left(\text{valid if } \frac{1}{R_s} \gg G_T \right).$$

The peaks in G_m - V_a curves in the depletion region are only observed with G_m in logarithmic plot. Typical example is shown in figures 6a and b.

5.2 EVALUATION OF N_{ss} AND V_s . — The conductance method of Nicollian and Goetzberger [1, 11-13] is suitable for the determination of interface state density N_{ss} in MIS structure with very thin oxide layer. The necessary equivalent circuits of the MIS diode for this evaluation are shown in figures 7c and d. The n devices are in depletion in low reverse bias (Fig. 5a), so the evaluation of N_{ss} is possible. The p devices are in inversion in reverse bias (Fig. 5b), and so we have not determined the interface state density in that case.

We found N_{ss} values typically $5 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ near the midgap for annealed LPCVD n devices and slightly higher for other n devices (around $10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$ near the midgap). These values are consistent with those used in modelling section (4.3.2).

The determination of surface potential has been carried out with Berglund integral [11] on low frequency C-V characteristics (30 Hz).

The V_{s0} value (surface potential at 0 V) have been evaluated by HF measurement [1]. We have found generally a positive value, depending on the samples between 50 mV and 150 mV for n devices and about 600 mV and 800 mV for p type devices.

Finally we have reported on figure 8 the experimental (solid lines) curves V_s vs. V_a for two samples (on n and p type substrate). The dashed line represents, for example, a theoretical V_s vs. V_a curve obtained by the simulation program of section 4.3.2. The agreement between experimental and theoretical results is generally satisfactory except for some not annealed LPCVD n devices which are in accumulation for zero volt bias.

Fig. 8. — Semiconductor surface potential vs. applied voltage V_a for a device on n type wafer : experimental (1) and theoretical (1') and for a device on p type wafer (2).

6. Conclusion.

In this paper Al-SiO₂-Si tunnel structures with thin oxide layers (30 Å) on n and p type wafers have been studied using measurements based on a microcomputer controlled system.

Interesting results may be deduced from the modelling of experimental I - V curves. The dispersion of these characteristics on the same wafer allow us to deduce dispersion of the most important physical parameters.

Thus, we have shown with the assumption of constant oxide thickness (typical value 30 Å) that the extreme experimental I - V curves can be fitted with an electronic affinity variation lower than 0.2 eV and an interface states density variation lower than $9 \times 10^{11} \text{ cm}^{-2}$.

This study is able to provide very useful information about the dispersion of the most important physical parameters of the Si-SiO₂ interface for very thin insulator layers. It would so be possible to improve the technological process in order to obtain good quality thin oxide layers.

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