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Negative capacitance in Aluminum/hydrogenated amorphous silicon nitride/n type crystalline silicon structure

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ABSTRACT

The dynamic admittance of Al/a-SiN_x:H/n-c-Si structure as function of bias voltage (V) and frequency (ω) have been investigated in wide ranges of frequency (300 Hz–1 MHz) and bias voltage (0–9 V) respectively at room temperature. Negative capacitance (NC) behavior has been observed at forwards bias voltages. It appears from value of bias voltage which depends on the frequency. This value corresponds on the current–voltage characteristics at the beginning bias voltage of thermionic emission regime of electrical conduction. Therefore the injection of electrons at a-SiN_x:H/n-c-Si interface by thermionic emission may be involved in the NC mechanism. In $C-\omega$ plot, a strong peak of NC has been observed at low-frequency, its intensity is about 110 times the geometrical capacitance. The frequency and the intensity of the NC peak show a linear variation versus a square root of bias voltage in semi logarithmic representation. The NC behavior is always accompanied with relatively high conductance "G/ω".

1. Introduction

Negative capacitance (NC) effects have been reported in a variety of electronic devices, such as p–n junctions [1] metal–semiconductor Schottky diodes [2–6], metal–insulator–semiconductor structures [7,8], heterostructures [9–13], far infrared detectors [14], UV photodetectors [15], light-emitting diodes and laser diodes [16] and organic light emitting diodes (OLED) [17–19]. Several authors have considered at the beginning, this effect as a measurement error. In order to confirm the NC is the diode's own characteristic, some authors [16,20] used a larger known capacitance in parallel with the tested diode, they find that $C'-V$ curve equivalent to translating the $C-V$ curve of the single diode to the positive capacitance value. So the negative capacitance of the diode can be confirmed considering the validity of the measurement for positive capacitance. In the same aim another test have been performed, a supposed parasitic series inductance has been calculated [20]. It has been found that values and frequency dependence of the calculated equivalent inductance are not compatible with parasitic elements that should have much lower values and much weaker frequency dependence at low frequencies. NC effect have been mainly attributed to the minority-carrier injection [21], sequential injection of electrons at the contact that takes place via intermediate states in the surface dipole layer [17], to the AC modulation of the occupation probability due to field-assisted hopping transitions between localized states [20], recombination [16]. Carrier capture and emission at interface states [14].

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In this study, the forward and reverse bias $C-V$ and $G/\omega-V$ characteristics of Al/a-SiN_x:H/n type c-Si structures have been investigated in a wide range of frequency (0.3 KHz–1 MHz) and applied bias voltage (−35 V to +10 V) at room temperature. We observed the NC at forward bias. The transition bias voltage to negative values of the capacitance depends on the measurement frequency. That's why we have made capacitance and conductance measurements as a function of frequency ($C-f$ and $G/\omega-f$) at various bias voltages. We observed a strong peak of NC at low frequency; its intensity is about 110 times the geometrical capacitance.

2. Experimental details

The hydrogenated amorphous silicon nitride thin film (a-SiN_x:H) are deposited by DC magnetron sputtering of silicon target with argon, hydrogen and nitrogen plasma mixture in a vacuum chamber. The films are deposited at 150 °C on two kinds of substrates: undoped silicon single crystal two faces polished (for infrared absorption and spectroscopic ellipsometry) and N type silicon for electrical measurements in sandwich configuration. The deposition condition parameters, film thickness and refractive index determined from spectroscopic ellipsometry (SE) are summarized in Table 1.

The ellipsometric spectra (Ψ, Δ) were collected over a spectral range of 1.3–5.0 eV at an angle of incidence of 75°, using a rotating-polarizer fixed-analyzer ellipsometer (Sopra, SE 2000). The chemical bonding nature of the films was investigated by infrared (IR) absorption measurements using a Perkin–Elmer Fourier transform infrared spectrophotometer with a resolution of 2 cm^{-1}, in a range from 400 to 4000 cm^{-1}. This characterization allows the determination of the chemical bonds present in the material and their configurations through the evolution of the absorption peaks related to the various vibration modes of Si—H and N—H bonds.

Thin aluminum electrodes are vacuum deposited on the thin film to perform the electrical measurements. The $C-V-f$ and $G-V-f$ measurements are carried out at room temperature in vacuum chamber at different frequencies using HP4192 A LF impedance analyzer (5 Hz–13 MHz). The test signal is fixed at 30 mV_{rms}. Current–voltage (I–V) characteristic is carried out using Keithley 617 electrometer at room temperature in vacuum chamber.

3. Results and discussion

In order to study the optical properties of the a-SiN_x:H deposited layer we performed spectroscopic ellipsometry (SE) measurements. The optical model used in this study is considerate as a mixture of three layers as depicted in Fig. 1. The phase1 and phase3 layers on the optical model represent the interface between the deposited material and the substrate and the surface roughness of the deposited layer. The Bruggeman dispersion model is used to describe the dielectric functions of these two layers. So the roughness layer is considered as a blending of vacuum and deposited material and the interface layer is considered as a blending of the deposited material and the mono-crystalline silicon substrate. The phase2 layer on the optical model represents the a-SiN_x:H main layer. It is modeled by the Tauc–Lorentz dispersion model. The statistical measure of the quality of fit attained was fairly high (regression coefficient, $R^2 > 0.995$) indicating a very good agreement between the fitted and the measured spectra. The Tauc–Lorentz energy band gap and refractive index is about 4.6 eV and 1.84, respectively.

Fig. 2 shows the FTIR absorption spectrum of investigated film after subtracting a fitted baseline and after taking into account the interference effects in the film. We can observe the presence of absorption bands due to Si—N, Si—H and N—H bonds. The frequency of Si—H band is 1190 cm^{-1}. At this frequency, the Si—H band is mainly composed of two components of frequencies 2175 and 2220 cm^{-1}; they are respectively due to Si—H vibrations in the configurations: "N—(SiH_2)—N" and "N—(SiH)=2N". We can notice that the two configurations do not contain Si—Si bonds [22,23]. This shows that the deposited a-SiN_x–H is stoichiometric or richer in nitrogen.

The small intensity of the Si—H band compared to that of the N—H band, the value of the refractive index of 1.84 and the value of Tauc–Lorentz gap of 4.6 eV confirm that the material is stoichiometric or richer in nitrogen.

Figs. 3 and 4 show respectively the measured $C-V$ and $G/\omega-V$ characteristics of the Al/a-SiN_x:H/n type c-Si structure as a function of bias voltage at the frequency range of 300 Hz–1 MHz at room temperature. We can see that the capacitance (C) and conductance (G/ω) plots are dependent on both the bias voltage and frequency. At negative bias voltages we can distinguish, in $C-V$ plot, two ranges: depletion and accumulation because of the flat band voltage shift to the negative bias voltages with respect to its theoretical value. This means that the interface and/or bulk of a-SiN_x:H are initially positively charged. When frequency decreases, we observe a shift of $C-V$ characteristic to the negative bias voltages and an increase of accumulation capacitance. This may be due to the fact that at high frequencies the charges at interface states cannot follow the AC signal contrary to low frequencies. At positive bias voltages the capacitance presents a peak. The position of this

Table 1
Deposition parameters and properties of the film.

Gas flow rate (sccm)			Total pressure (Pa)	Temperature (°C)	Refractive index	Thickness (μm)	deposition rate (A°/sec)
Ar	N_2	H_2					
4.88	4.2	2.56	≈1	150	1.84	0.524	4.13