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Electrical characterization and carrier transportation in Hf-silicate dielectrics using ALD gate stacks for 90 nm node MOSFETs

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ABSTRACT

Metal-oxide-semiconductor capacitors (MOSCs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) incorporating hafnium silicate (Hf-silicate) dielectrics were fabricated by using atomic layer deposition (ALD). The electrical properties of these Hf-silicate thin films with various postnitridation annealing (PNA) temperatures were then examined to find the best nitridation condition. It is found that the best conditions to achieve the lowest gate leakage current and best equivalent oxide thickness (EOT) are when PNA is performed at 800 °C in NH_3 ambient for 60 s. To understand the obtained film, carrier transportation mechanisms, the temperature dependence of the leakage current was measured from 300 K to 500 K for both gate injection and substrate injection. The result reveals that the leakage mechanisms involve Schottky emission at high temperature and low electrical field and Poole–Frenkle emission at low temperature and high electrical field. The barrier heights of poly-Si/Hf-silicate and Hf-silicate/Si interfaces extracted from Schottky emission are 1.1 eV and 1.04 eV, respectively. The interface traps per unit area, the mean density of interface traps per area and energy and the mean capture cross-section are determined about 8.1×10^{10} cm^{-2}, 2.7×10^{11} cm^{-2} eV^{-1} and 6.4×10^{-15} cm^{-2} using charge pumping method.

1. Introduction

The SiO_2-based gate dielectric is toward its physical limits due to its gate leakage current [1–3] and reliability concerns [4]. In order to solve these issues, the so-called high-κ dielectrics have been extensively investigated, and among which hafnium silicate (Hf-silicate) has been suggested as one of the most promising gate dielectrics to replace SiO_2 [5,6]. This is because Hf-silicate has been reported to have many advantages [7], such as relatively high dielectric constant, satisfied thermal stability, better leakage characteristics and lower mobility degradation. To enhance the properties of Hf-silicate, nitridation has been used to improve the homogeneity and dielectric constants as well as to reduce the boron penetration and trapped charges [8–10]. Based on the above understanding, this work further fine tuned the nitridation conditions and obtained that better quality of Hf-silicate should be through postnitridation annealing (PNA) at 800 °C and for 60 s. To understand the obtained film quality, the study thereafter focused on finding the carrier transport mechanisms, electron effective mass (m^*) and barrier heights under various operating temperatures. Although Poole–Frenkel (P–F) conduction has been found in the gate leakage [11], our study reveals that Schottky emission also involves in the carrier transportations. Moreover, the barrier heights to be discussed in this work are effective values which include the effects of interfacial layers. In the last part of this paper, charge pumping in cooperation with *I–V* methods was applied to find the interface quality and the mean capture cross-section. The results are indicating that they are within acceptable range and have the potential to be applied in mass production.

2. Experiments

In this work, p-type silicon wafers were used as the starting substrate. Following the cleaning procedures, 1 nm rapid thermal (RT-N_2O) plasma oxidation was performed. Next, 2 nm Hf-silicate

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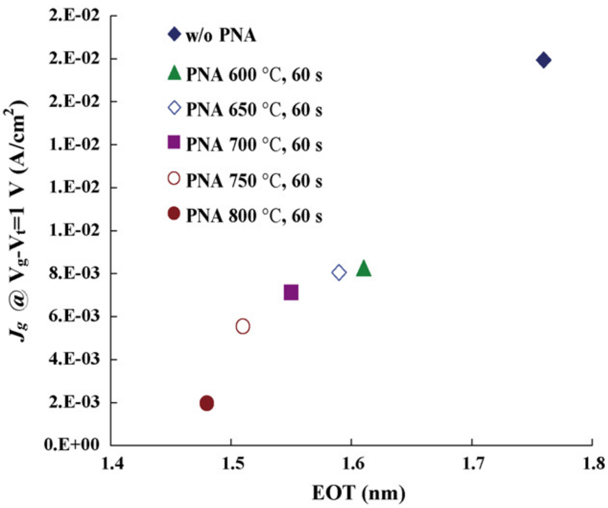

Fig. 1. J_g versus EOT with various PNA temperatures.

(Hf:Si = 1:1) thin film was deposited by atomic layer deposition (ALD). The PNA temperatures were performed from 600 °C to 800 °C at NH_3 ambient for 60 s. Finally, the 150 nm poly-Si was deposited as top gate electrode. The electrical properties of poly-Si/Hf-silcate/Si metal-oxide-semiconductor capacitors (MOSCs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) were characterized by *I–V* measurements using HP 4156C.

3. Results and discussion

Fig. 1 shows gate leakage current density (J_g) versus equivalent oxide thickness (EOT) with various PNA temperatures from 600 °C to 800 °C in NH_3 ambient for 60 s, where PNA 800 °C treatment exhibits the lowest gate leakage current density and best EOT. Gate leakage current density and EOT are 1.9×10^{-3} A/cm^2 and 1.48 nm, respectively. The higher dielectric constant and lower gate leakage current for HfSiON can be attributed to the nitrogen atoms keeping the homogeneity of the thin films through the high temperature PNA treatment [8].

In order to understand the carrier transportation mechanisms of the obtained optimal Hf-silicate dielectrics, temperature dependence of gate leakage current density was investigated from 300 K to 500 K both under gate injection and substrate injection, as shown in Fig. 2.

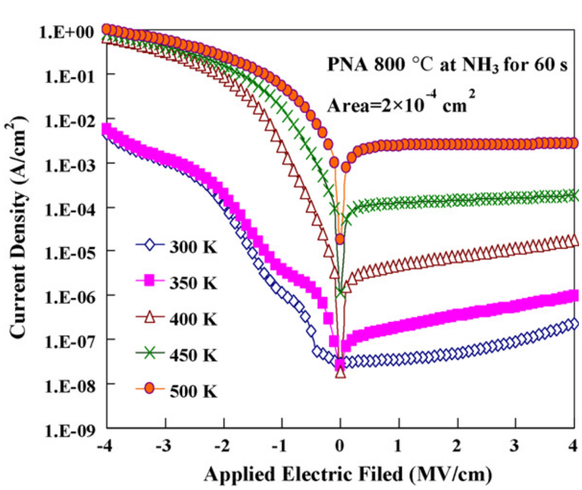

Fig. 2. Characteristics of *J–E* plots for Hf-silicate MOSCs at various temperatures.

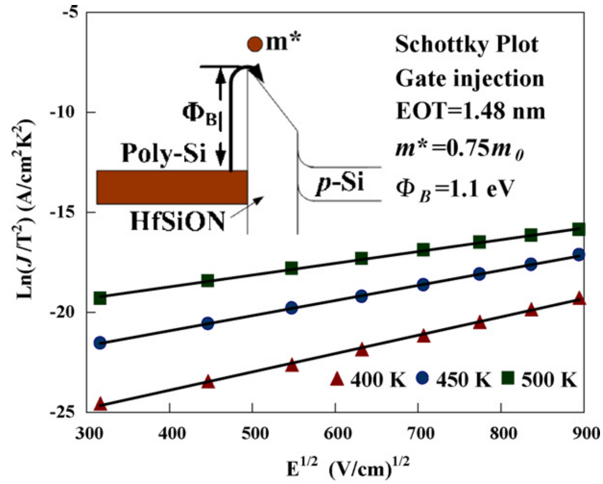

Fig. 3. Characteristics of Schottky emission in the region of high temperature and low field under gate injection. The inset is the band diagram. $\Phi_B = q\phi_B$ is the Schottky barrier height.

After analysis, it is found that the main carrier transportation mechanisms should be Schottky emission and Poole–Frenkel emission. To elucidate these, a brief review of the mechanisms is provided as the follows. It is well known that Schottky emission can be expressed as [12]:

$$J = A^* T^2 \exp\left[\frac{-q(\phi_B - \sqrt{qE/4\pi\varepsilon_i})}{kT}\right] \quad (1)$$

where A^* is the effective Richardson constant and $A^* = 4\pi\, q(m^*)k^2/h^3 = 120(m^*/m_0)$, T is the absolute temperature, q is the electronic charge, $q\phi_B$ is the Schottky barrier height, E is the electric field, k is the Boltzmann's constant, h is the Planck's constant, ε_i is the dielectrics constant, m_0 is the free electron mass and m^* is the electron effective mass in Hf-silicate.

For standard Schottky emission, a plot of $\ln(J/T^2)$ versus $E^{1/2}$ should be linear. Experimental data in the region of high temperature (400–550 K) and low electric field (≦0.8 MV/cm) fit Schottky emission theory very well for both under gate injection and substrate injection as shown in Figs. 3 and 4.

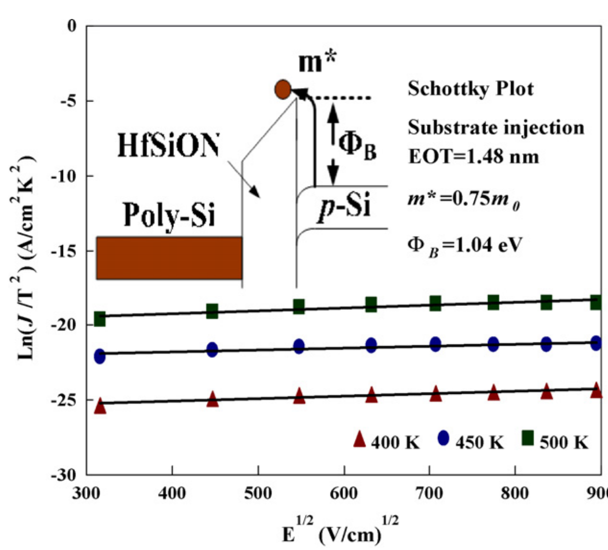

Fig. 4. Characteristics of Schottky emission in the region of high temperature and low field under substrate injection. The inset is the band diagram. $\Phi_B = q\phi_B$ is the Schottky barrier height.