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Research paper

Effect of arsenic doping on charge relaxation process in silicon nitride film for capacitive RF MEMS switch application

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ABSTRACT

In this work, effects of arsenic doping on dielectric charging/discharging of silicon nitride (SiN) films prepared by low-pressure chemical vapor deposition (LPCVD) have been investigated for the application of capacitive RF MEMS switches. The dielectric charging/discharging processes have been evaluated in an analogous metal–insulator–semiconductor (MIS) structure by capacitance-voltage (C-V) characterization. Arsenic doping was applied to modify the distribution of energy states in the band gap of thin film SiN. The dielectric discharging behaviors were studied with different discharge time under a dc bias. The C-V curves show that low dielectric charging has been observed in the SiN films after arsenic doping. The generation and recombination centers were introduced into the band gap of thin films SiN, and the dielectric charging is modified and further controlled by the doping technology. The arsenic-doped thin films SiN exhibit excellent dielectric properties to meet the application requirement of capacitive RF MEMS switches.

1. Introduction

Capacitive Radio frequency (RF) micro-electro-mechanical-systems (MEMS) switches, as one of the most important MEMS devices, are expected to be one of the most promising components applied in cell phones, phased-array radar and other equipment due to the merits of low insertion loss, high isolation and low power consumption [1,2]. However, the commercialization is still hindered by dielectric charging induced failure, which is considered as a primary reliability issue [3]. To improve the reliability of capacitive RF MEMS switches, considerable efforts have been devoted to the study of affecting factors of dielectric charging of thin films SiN, including dielectric thickness [4,5], deposition conditions [6,7], applied voltage and working temperature [8,9]. Moreover, huge efforts have been made for developing the technology of mitigating dielectric charging, for instance, advanced actuation waveforms [10], innovative structures [11,12] and nanostructured dielectrics [13]. Recently, ultrananocrystalline diamond films show unique physical and electrical properties, which also provide a potential solution to reliability issues related to dielectric charging [14].

General speaking, dielectric charging is attributed to both charge injection and charge relaxation. In our previous work [15], we have found that dielectric discharging properties were improved due to the introduction of donor levels of P and B in the thin films SiN. The doping method is an effective way to modify the band gap states and to affect the charging and discharging properties. Recently, it was reported that electrical characteristics of ZnO films are strongly affected by arsenic (As) dopant according to photoluminescence and Hall Effect measurements [16,17]. However, the charging and discharging study of silicon nitride films before and after element As doping has not investigated yet. The objective of this study is to modify band gap of the thin films SiN by arsenic dopant, and we expect that donor levels of element As play an important role for fast discharging process as well.

2. Experiments

2.1. Preparation

The switch structure is similar to a metal-insulator-metal (MIM) capacitor and the MIM models have been used to investigate dielectric charging [9]. In this work, the dielectric charging/discharging behaviors were evaluated by MIS structures, because the charging characteristics of dielectrics were easily accessed by measuring the *C-V* curve shift at room temperature with a MIS structure. Although the MIS model was different from the MIM structure, many of these surface or interface states are fast states compared with bulk states, which make a negligible contribution to the charge accumulation in the dielectric, and the hole injection was neglected when positive bias voltage was applied to the metal electrode. In Ref. [18], we demonstrated that the effective trapped

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charges shown the same form of expression in MIM and MIS models, and the dielectric charging characteristics of the MIS model were accessed by analyzing the *C-V* curve shift at room temperature. As shown in Fig. 1, the test MIS devices were fabricated on n-type (100) single side polished silicon (Si) wafers. The resistivity and phosphorus doping concentration is about 3 Ω·cm and 10 E15/cm^3. The film quality of SiN deposited by LPCVD was much better than that deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) due to different deposition condition, and the doping has little effect on dielectric charging and discharging processes in PECVD SiN films [15]. Therefore, the insulator in the MIS structure is SiN dielectric films with thickness of about 3000 Å deposited by LPCVD, and the reaction gases (NH_3:SiH_2Cl_2) flow ratio and the temperature are 4:3 and 780 °C.

To modify distribution of the energy states in the band-gap of the dielectric thin films SiN for improving dielectric charging/discharging behaviors, arsenic ions were implanted into the SiN dielectric layers of the three samples with doping concentration of 0 (virginal), 1 E13/cm^3 (low doping) and 5 E14/cm^3 (high doping) by ion implantation technology. Table 1 lists the parameters of the ion implantation process for the three samples.

Then Al metal electrode with a circle radius of 0.5 mm was deposited on the top surface of the SiN dielectric film. On the backside of the Si wafer, an Al metal film was also sputtered for good ohmic contact between the sample and chuck plate of the measurement setup.

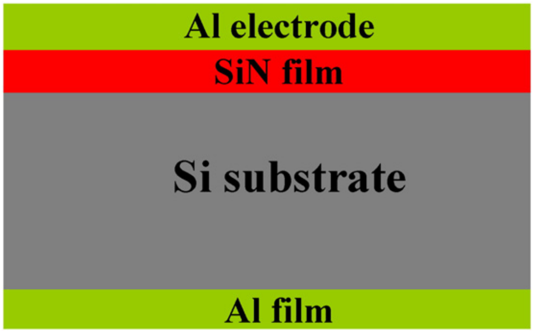

Fig. 1. Schematic cross-sectional views of the MIS structures.

2.2. C-V measurement

The amount of injected charges in the dielectric of MIS structure was evaluated by *C–V* measurement [18]. The flat band voltage (V_{FB}), which was estimated by corresponding flat band capacitance (C_{FB}) [15] in the *C–V* curves, was a negative voltage applied between the metal and semiconductor to achieve the flat band and a function of the total amount of space charges in the dielectric. The shifts of *C-V* curves after the dc bias towards the left or right indicate that net positive or negative charges injected into the dielectric. In the *C-V* measurement, the quantity of trapped charges in the dielectric, N_t, is estimated by

$$qN_t = C_0\Delta V_{FB} \tag{1}$$

where C_0 is the biggest capacitance shown in the *C-V* curve, ΔV_{FB} is the flatband voltage shift caused by the injected charges.

The space charges were introduced into thin film SiN by electrically stressing the MIS structure with a 50 V dc bias for 300 s, which resulted in an electrical field over 1.66 MV/cm across the dielectric film with thickness ~0.3 μm. Then the charge relaxation processes were monitored by *C-V* measurement through different discharge time by comparing the *C–V* curves measured before and after charge injection with a Keithley 4200-SCS Semiconductor Characterization System.

Table 1
The ion implantation parameters for the three samples.

No.	SiN film thickness nm	Ion	Implantation energy KeV	Implantation depth nm	Implantation concentration cm^{-3}
1	300	Virginal	0	0	0
2	300	As	140	130	1E13
3	300	As	140	130	5E14

3. Results and discussion

3.1. Before charging

The *C-V* curves were measured by performing a voltage sweep from −30 V to 30 V with frequency ~1 MHz. Fig. 2 shows the *C-V* curves measured on virginal and arsenic-doped samples without applying dc bias voltage. The negative value of the V_{FB} represents successful distributions of positive space charges. The large absolute value of V_{FB} suggests high space charges, which the virginal sample shows the largest number of space charges, followed by the high-doped samples, and the low-doped sample contains the lowest number of space charges. The amount of space charges in the dielectric is influenced by the doping process, because the doping impurities would likely combine with the dangling bonds to repair the structural defects in the dielectric. Therefore, the number of positive space charges in the dielectric was decreased after arsenic doping.

However, there are more positive charges in high-doped samples than that in the low-doped samples. As shown in Fig. 2, it is clearly seen that the flatband voltage shift ΔV_{FB} between the virginal sample and low-doped sample is about 0.78 V, while the flatband voltage shift ΔV_{FB} between the virginal and the high-doped sample is only about 0.31 V. The main reason is that the excess impurities may introduce new structural defects and produce more positive charges at high doping levels.

3.2. After charging

After measuring the C-Vs without electrical stress, all samples were electrically stressed with 50 V dc bias for 300 s, while the Al electrode was connected to the positive polarization. As the dc bias stress (charge injection) was released and waited for 0, 2, 5, 10, 30 and 60 min respectively, the C-V measurements were presented as function of waiting time in Fig. 3.

Fig. 3 a–c shows the *C-V* curves of virginal, low-doped and high-doped thin film SiN before and after charge injection. Overall, more

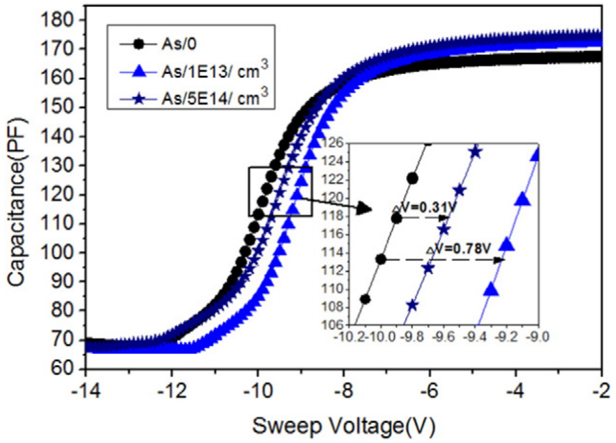

Fig. 2. C—V curves measured on (s) the virginal MIS devices with arsenic doping concentration of 0, 1 E13/cm^3 and 5 E14/cm^3.