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Formation of Si:CP layer through in-situ doping and implantation process for n-type metal–oxide–semiconductor devices

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ABSTRACT

In this study, the effect of Cluster Carbon implantation and thermal annealing for recrystallization on the properties of phosphorus doped Si (Si:P) epitaxial films was investigated. Several Cluster Carbon implantation conditions and recrystallization annealing techniques based on solid phase epitaxy with rapid thermal annealing (RTA), spike RTA (sRTA), and millisecond laser annealing have been employed. It was found that a high substitutional carbon concentration can be achieved by laser annealing while high thermal budget annealing caused the loss of almost half of the substitutional carbon. The reduction of end of range defects and stacking faults/dislocation loops at the surface of carbon and phosphorus doped Si (Si:CP) layers through the use of cold implantation and fewer implantations was confirmed. Although sRTA activates phosphorus, additional laser annealing improves phosphorus activation further in the Si:CP layer. The phosphorus profile is abrupt with Cluster Carbon implantation when compared to no carbon implantation.

1. Introduction

Strain engineering has been adopted as a key element for state-of-the-art high performance complementary metal–oxide–semiconductor field-effect transistor (MOSFET) devices. Recently, embedded carbon doped Si (e-Si:C) in the source and drain (S/D) region technology for enhanced nMOSFET drive current has been reported [1]. The enhanced electron mobility in silicon thus boosts the nMOS device performance. Growth of epitaxial in-situ carbon and phosphorus doped silicon (Si:CP) is believed to be one of the most promising technologies to provide tensile stress in the nMOS channel leading to enhanced electron mobility and lower S/D resistance. The approach for forming e-Si:C S/D with recessed S/D and strained e-Si:C films with a high substitutionally incorporated carbon concentration ($[C]_{sub}$) using selective epitaxial process requires complicated processes and integrations [2–5]. Therefore, creation of (Si:CP) layers through phosphorus and carbon implantation followed by a recrystallization annealing process could be another candidate to achieve Si:CP S/D structure with relatively simple process integration [6,7]. The combination of implantation and recrystallization annealing processes poses challenges, however, in the simultaneous pursuit of growing strained Si:CP films with high $[C]_{sub}$ (>1%) and removing implant damage because of the low equilibrium solid solubility of carbon in Si (~3×10^{17} cm^{-3}) and low thermal budget requirement for sub-14 nm technology nodes. There is also a trade-off between low sheet resistance and strain in the above process due to the competition by both phosphorus and carbon to occupy silicon substitutional sites [8,9].

In this study, we have investigated the effect of combining both the in-situ phosphorus doping and carbon implantation processes to form (Si:CP) layers. Cluster Carbon implantation is known to produce an amorphous layer (helps in the anneal regrowth process) and create a strained Si:C layer (helps to boost mobility in the channel) [10,11]. The properties of Si:P epitaxial films due to carbon implantation and recrystallization annealing are studied.

2. Experimental details

In-situ doped Si:P films were 50 nm thick with a phosphorus doping concentration of 4×10^{20} atoms/cm^3 and epitaxially grown on p-type Si(001) substrates in a commercial 300 mm reduced-pressure chemical vapor deposition reactor. The phosphorus concentration profile is constant along the depth of the film and forms an abrupt junction with the substrate as shown in Fig. 1. For our studies, several samples were made with multiple implantation conditions to get 1.2% carbon atomic concentration using single, double, and triple carbon implantation energies and doses. The implantations were performed at room temperature (RT) and −30 °C without any tilting and rotation. The implantation conditions were as described below: (I) 4 keV/5.0 × 10^{14} cm^{-2} + 8 keV/1.0 × 10^{15} cm^{-2} + 19 keV/4.2 × 10^{15} cm^{-2}C equivalent (triple carbon implantation for a boxlike profile), (II)

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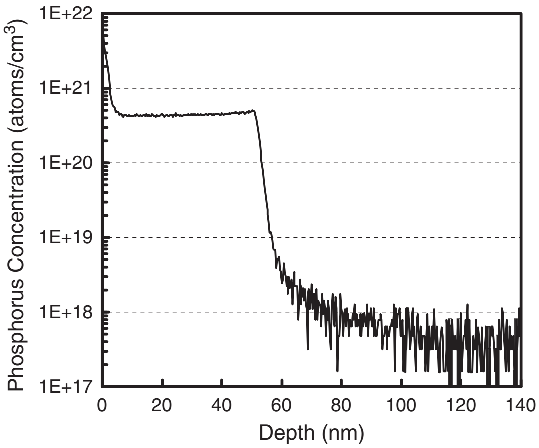

Fig. 1. The phosphorus concentration profile measured with Secondary Ion Mass Spectrometry (SIMS) showing constant concentration along the depth of the film and an abrupt junction.

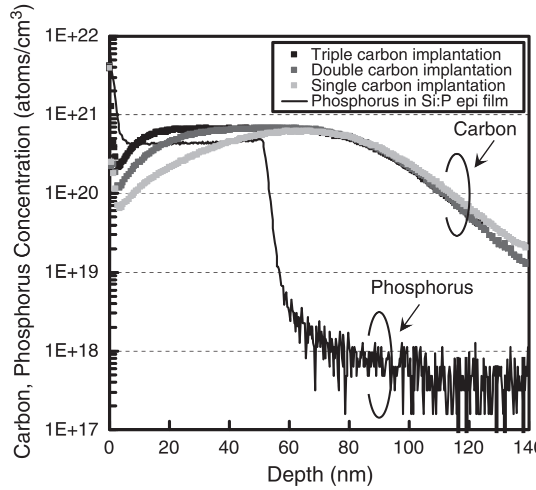

Fig. 2. The carbon concentration profile for each implantation conditions measured with SIMS showing boxlike profile along the depth of the film for triple and double carbon implantation.

8 keV/1.0 × 10^{15} cm^{-2} + 19 keV/4.2 × 10^{15} cm^{-2}C equivalent (double carbon implantation for a boxlike profile) and (III) 19 keV/4.2 × 10^{15} cm^{-2}C equivalent (single carbon implantation). The Cluster Carbon ion $C_7H_7^+$ was chosen for implantations at 8 keV/1.0 × 10^{15} cm^{-2} and 4 keV/5.0 × 10^{14} cm^{-2}C equivalent, $C_3H_3^+$ was chosen for implantation at 19 keV/4.2 × 10^{15} cm^{-2}C equivalent. Boxlike profile of carbon is required to achieve a thicker Si:CP layer with uniform strain through the film thickness direction. Cluster Carbon source species and the C+ equivalent energy and dose for each implantation conditions are shown in Table 1. Fig. 2 also shows the carbon profiles for each implantation condition. The boxlike profile of carbon can be achieved by triple and double implantation conditions. Recrystallization—including thermal annealing based solid phase epitaxy—was achieved using rapid thermal annealing (RTA) at 950 °C for 5 s and spike RTA (sRTA) in the temperature range from 1000 to 1050 °C followed by millisecond (ms) laser annealing at 1250 °C. The properties of the processed films were characterized using several techniques. The substitutional carbon concentration and quality of the epitaxial films (and thickness) were investigated by high resolution X-ray diffraction (HR-XRD) using a BedeMetrix-L in triple-axis mode with a sealed Cu-Kα tube. The primary beam was conditioned using a multilayer X-ray mirror, 2-bounce Ge (004) beam conditioner. The total carbon (substitutional carbon + interstitial carbon) concentration and phosphorus concentration depth profiles were determined by secondary ion mass spectroscopy (SIMS) using Cameca IMS Wf instrument with 500 eV Cs^+ as the primary ion. Microstructure analysis was performed by transmission electron microscopy (TEM). The TEM samples were imaged at 200 kV in a FEI F20 TEM microscope. Electrical properties of activated phosphorus in recrystallized Si:CP films were examined by a linear four-point probe method.

3. Results and discussion

The sheet resistance (Rs) results after 1.2% triple carbon implantations with recrystallization annealing and additional laser annealing are shown in Fig. 3. The Rs results of Si:P epi wafers with no carbon implantations are plotted as reference. The results show that the Rs values are lower for Si:P epi wafers with no carbon implantations (117 Ω/sq) with no anneal and drops to 62 Ω/sq with sRTA at 1025 °C. Introducing additional laser annealing shows only a small reduction in Rs, whereas in the case of the samples which received carbon implantations with RTA at 950 °C for 5 s and sRTA at 1025 °C, the reduction in Rs was about 15% by introducing additional laser annealing. This result suggests that the reduction in Rs by additional laser annealing is due to the increase in the phosphorus activation ratio, as any phosphorus diffusion by laser annealing was not detected. The increase in Rs is observed in the Si:CP layer after recrystallization annealing compared to Si:P with no carbon implantations. This suggests that the formation of electrically active phosphorus is prevented by the C incorporation. Fig. 4 shows the Rs of the phosphorus activation in Si:CP layer implanted at −30 °C with sRTA at 1025 °C followed by 1250 °C laser annealing as a function of implanted total carbon dose. The Rs increased with increasing implanted carbon dose which corresponds to the carbon concentration at the Si:CP surface region. It is confirmed that the Rs of the phosphorus activation in the Si:CP layer can be improved by additional laser annealing.

Fig. 5 shows 004 ω-2 scan from 1.2% triple carbon implantations with recrystallization annealing. The scan has two main diffraction peaks: an intense peak from the Si substrate located at 0″ and a lower intensity peak from the Si:CP layer. The positions of these two peaks correspond to the out-of-plane lattice parameter/strain in the layer. The clear thickness fringes around the main Si:CP peak indicate a high-quality Si:CP layer with good crystallinity. It was confirmed that

Table 1
Cluster Carbon source species and C^+ equivalent energy and dose for each implantation conditions.

	Cluster Carbon ion (C+ equivalent)		
	$C_7H_7^+$	$C_7H_7^+$	$C_3H_3^+$
Triple carbon implantation	4 keV/5.0 × 10^{14} cm^{-2}	8 keV/1.0 × 10^{15} cm^{-2}	19 keV/4.2 × 10^{15} cm^{-2}
Double carbon implantation		8 keV/1.0 × 10^{15} cm^{-2}	19 keV/4.2 × 10^{15} cm^{-2}
Single carbon implantation			19 keV/4.2 × 10^{15} cm^{-2}