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Carbon Profile Engineering for Silicon-Carbon Source/Drain Stressor Formed by Carbon Ion Implantation and Solid Phase Epitaxy

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Abstract

We explore carbon profile engineering for silicon-carbon (Si:C) source/drain (S/D) stressors formed by carbon implantation and Solid-Phase Epitaxy (SPE). A steep retrograde carbon profile is investigated, where the C concentration is low near the S/D surface and high approximately 15 nm beneath the surface. The retrograde C profile alleviates carbon-induced dopant deactivation near the surface of the phosphorus-doped S/D. Reduced surface C concentration also reduces the incorporation of C in nickel silicide which can increase the sheet resistance R_S. Carbon-implanted samples were annealed using various SPE conditions, and their R_S and substitutional carbon concentration C_{sub} were characterized. High C_{sub} can be achieved with SPE temperatures lower than 800 ˚C. A retrograde C profile also achieves a lower R_S for a given C_{sub} than a uniform C profile.

1. Introduction

Silicon-carbon (Si:C) source/drain (S/D) stressors have been extensively studied for performance enhancement in n-channel MOSFETs [1]-[8]. The lattice mismatch between Si:C and Si can be exploited to induce tensile strain in the channel for enhancing electron mobility and drive current. However, carbon-induced deactivation of dopants in the S/D and the associated increase in S/D resistance is an issue which offsets the benefits of strain from the Si:C stressor [8].

In this paper, we explore the concept of a retrograde carbon profile in Si:C stressors formed by carbon implant and Solid Phase Epitaxy (SPE). The C profile is spatially decoupled from an overlying region that is heavily doped with phosphorus [Fig. 1(a)]. Reduced C concentration in the surface of the S/D helps achieving a high dopant activation, which is expected to be important for achieving a low contact resistance. We investigate the sheet resistance R_S and substitutional carbon concentration C_{sub} of Si:C stressors with retrograde C profile or uniform C profile for various SPE conditions.

2. Formation of Retrograde Carbon Profile

8-inch boron-doped bulk Si (001) wafers were used as starting substrates. After a Ge pre-amorphization implant, C^+ was implanted. All wafers received a 2×10^{15} cm^{-2} phosphorus implant at 1 keV which formed a 10 nm n-type layer on the Si surface. Heavy n-type doping at the surface is needed for achieving low contact resistance. All implant process conditions, including the implant energies and doses of Ge, C, and P, are documented in Table I. For the split with retrograde carbon (Retrograde C) profile which is spatially decoupled from the P profile, a single C^+ implant (9 keV, 3×10^{15} cm^{-2}) was used to form a 30 nm thick Si:C layer beneath a 15 nm thick Si surface layer [Fig. 1(a)].

Control wafers with uniform carbon (Uniform C) profile within the top 45 nm of Si were also fabricated for comparison [Fig. 1(b)]. For the control wafers, multiple C^+ implants (3.3×10^{15} cm^{-2} at 9 keV, 6×10^{14} cm^{-2} at 3 keV, and 2.4×10^{14} cm^{-2} at 1 keV) were employed to achieve uniform carbon concentration in the top ~45 nm of Si. The Uniform C profile overlaps with the P profile for control wafers.

SPE was performed for the as-implanted samples using Rapid Thermal Processing (RTP). SPE temperature was varied from 650 to 950 ˚C and the annealing time ranged from 30 to 120 s. R_S was measured using a four-point probe. Crystal quality and C_{sub} were examined using High Resolution X-Ray Diffraction (HRXRD).

3. Results and Discussion

The R_S values achieved with various SPE temperatures and durations are plotted in Fig. 2. When the SPE temperature is below 800 ˚C, the R_S of samples with retrograde C profile is more than 30% lower than the control samples with uniform C profile. The decreased R_S is attributed to the decoupling of C profile from the heavily doped surface and the reduced dopant deactivation. However, the absolute R_S is larger than 300 Ω/□ in this temperature range. The low temperature SPE process is insufficient for achieving high dopant activation, but this could be circumvented with a subsequent flash or laser anneal (not investigated in this work). With higher SPE temperatures, i.e. 950 ˚C for 60 s, the R_S can be lowered to 130 Ω/□, but the difference in R_S between the sample with retrograde C profile and the control sample becomes smaller. This is due to the upward C diffusion into P-doped region which causes dopant deactivation (Fig. 3). SPE temperatures higher than 950˚ C gives essentially the same R_S for both sample types. Fig. 4 shows the R_S of NiSi formed under various silicidation conditions. Lower R_S can be achieved with retrograde C profile.

In order to check the crystalline quality of Si:C, five samples from each split (Fig. 5 and 6) were characterized by HRXRD. C_{sub} was also extracted from the XRD spectra by curve-fitting with simulation data. With a 700 ˚C 120 s SPE, C_{sub} is 1.5% for the sample with retrograde C profile. Almost full activation of all the C concentration was achieved, i.e. 100% substitutionality. Note that samples with retrograde C profiles can achieve comparatively lower R_S while preserving high $C_{sub.}$ As the SPE temperature is raised slightly above 700 ˚C, C_{sub} decreases due to carbon atoms moving from substitutional to interstitial sites (Fig. 3). When the SPE temperature is above 800 ˚C, C_{sub} drops very substantially. A 900 ˚C 40 s SPE gives a low C_{sub} for both C profiles (Fig. 7) (below 0.5%), which is not ideal for channel strain engineering. The comparatively lower C_{sub} in samples with retrograde C profile should also be contributed by a lower total carbon dose.

Fig. 8 summarizes the R_S and C_{sub} values obtained from the same set of samples in Fig. 5 and 6. The retrograde C profile achieves a lower R_S for a given C_{sub} or a higher C_{sub} for a given R_S as compared with a uniform C profile.

4. Conclusions

We investigated Si:C S/D stressors having a retrograde carbon profile formed by carbon implant and Solid Phase Epitaxy. Compared with Si:C S/D with a uniform C profile, a retrograde carbon profile that is decoupled from the heavy dopant concentration in the surface of the S/D alleviates carbon-induced dopant deactivation, which may be important for forming low resistance contacts. Si:C with a retrograde C profile can achieve a lower sheet resistance than control samples with uniform C profile for SPE temperatures below 800˚C.

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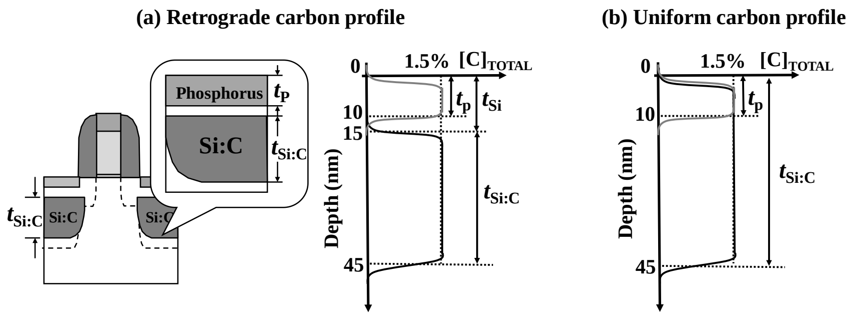

Table I. The implant process conditions for achieving retrograde C and uniform C profiles.

	Retrograde C Profile	Uniform C Profile
Pre-amorphization Implant	Ge 30 keV 5×10^{14} cm^{-2}	Ge 30 keV 5×10^{14} cm^{-2}
Carbon Implant	C 9 keV 3×10^{15} cm^{-2}	C 9 keV 3.3×10^{15} cm^{-2}; C 3 keV 6×10^{14} cm^{-2}; C 1 keV 2.4×10^{14} cm^{-2}
Dopant Implant	P 1 keV 2×10^{15} cm^{-2}	P 1 keV 2×10^{15} cm^{-2}

Fig. 1. (a) Schematic illustration of a planar MOSFET with retrograde carbon (Retrograde C) profile in S/D. t_{Si} is defined as the thickness of surface Si layer with negligible carbon concentration. t_P is defined as the distance between the 1×10^{18} cm^{-3} phosphorus concentration contour and the silicon surface, which can be interpreted as the thickness of the phosphorus-doped surface layer. (b) Control wafers have a uniform carbon profile.

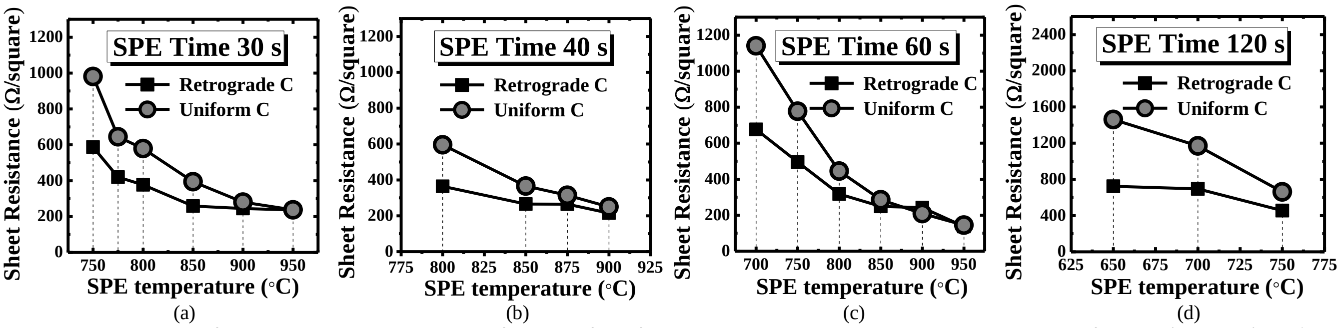

Fig. 2. Sheet resistance of samples with retrograde C and uniform C profiles after various SPE anneals. The SPE temperature is varied from 650 ˚C to 950 ˚C and the annealing time is fixed at (a) 30 s, (b) 40 s, (c) 60 s, or (d) 120 s.

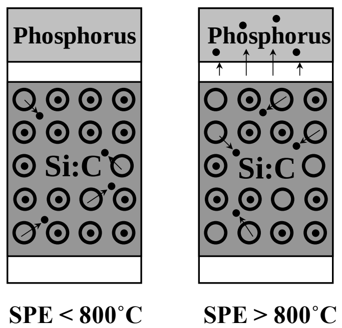

Fig. 3. Illustration of carbon atoms diffusion with SPE temperature below and above 800˚C. The circles represent lattice sites for substitutional carbon atoms and the black dots represent the carbon atoms.

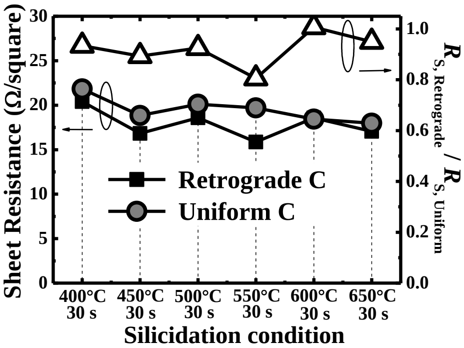

Fig. 4. NiSi sheet resistance of samples with retrograde C and uniform C profile versus various silicidation conditions. Lower sheet resistance can be achieved with the retrograde C profile.

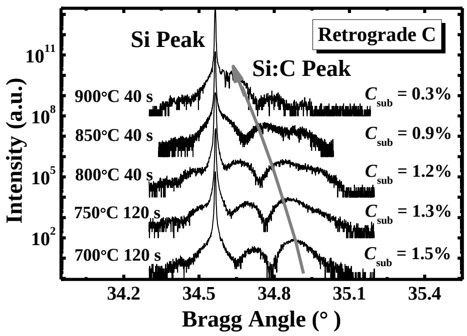

Fig. 5. HRXRD spectra of samples with retrograde C profiles after various SPE anneals. The Si:C peak moves toward the Si peak as the SPE temperature is increased. This indicates that substitutional carbon concentration is smaller for high SPE temperatures.

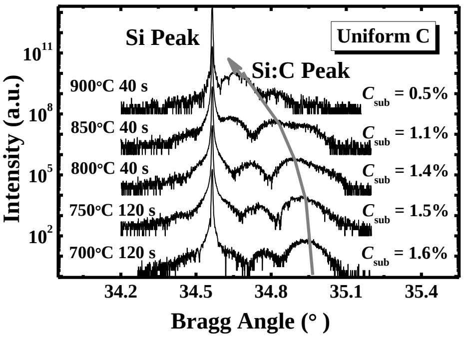

Fig. 6. HRXRD spectra of samples with uniform C profiles after various SPE anneals. The sample annealed at 700 ˚C for 120 s shows the highest C_{sub}.

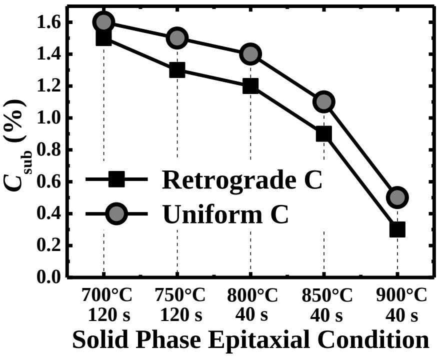

Fig. 7. Substitutional carbon concentration (C_{sub}) versus SPE conditions. C_{sub} is lost at high SPE temperatures.

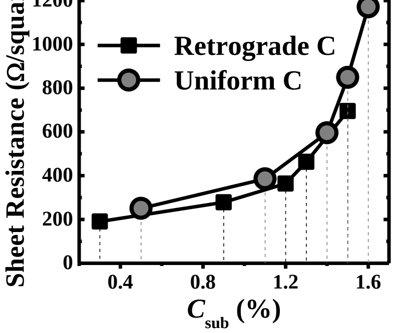

Fig. 8. Samples with retrograde C profile achieve a lower sheet resistance for a given C_{sub} as compared with samples with a uniform C profile.