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N-Channel MOSFETs with Embedded Silicon-Carbon Source/Drain Stressors formed using Novel Cluster-Carbon Implant and Excimer Laser-Induced Solid Phase Epitaxy

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ABSTRACT

We report for the first time the use of a novel cluster-carbon ($C_7H_7^+$) implant and pulsed excimer laser-induced solid phase epitaxy (SPE) technique to form embedded Silicon-Carbon (Si:C) source/drain (S/D) stressors. A substitutional carbon concentration C_{sub} of ~1.1% was obtained. N-FETs integrated with embedded Silicon-Carbon (Si:C) S/D stressors formed using the novel Cluster-Carbon implant and pulsed laser anneal technique demonstrate improvement in current drive I_{DSAT} of 15% over control n-FETs formed without carbon implant. I_{OFF}–I_{DSAT} comparison shows a 16% I_{DSAT} enhancement for n-FETs with embedded Si:C S/D at an I_{OFF} = 1×10^{-7} A/μm. Cluster-Carbon implant and laser anneal presented in this work is a simple and cost-effective approach to boost I_{DSAT} performance, and is a promising option for strain-engineering in advanced technology nodes.

INTRODUCTION

Embedded Silicon-Carbon (e-Si:C) source/drain (S/D) stressors formed by S/D recess-etch and selective epitaxy have been extensively explored in bulk [1]-[2] and SOI [3] transistors. For ultra-thin-body [4] or multiple-gate [5] device architectures, integration of embedded S/D stressors faces challenges in performing S/D recess etch. An alternative approach to form Si:C S/D through introduction of carbon by ion implant followed by solid phase epitaxy (SPE) was recently demonstrated [6]. However, there is no work on use of Cluster-Carbon (cluster-C) implant for forming Si:C S/D in devices. Cluster-C could achieve high carbon doses at high throughput. Moreover, laser anneal on carbon-implanted S/D has not been explored as well.

In this paper, we report the first demonstration of the use of a novel Cluster-Carbon implant and its combination with laser anneal (LA) to form e-Si:C S/D n-FETs. Since Cluster-C implant amorphizes the Si surface, Ge pre-amorphization implant (PAI) can be eliminated. In addition, it enables precise control of junction depth, and simultaneously introduces a high dose of C at high throughput. The pulsed laser anneal (PLA) achieves laser-induced SPE of Si:C with high dopant activation well above the maximum solid solubility limit. Strained n-FETs with Si:C S/D having a substitutional carbon concentration (C_{sub}) of 1.1% were fabricated, showing 15% drive current enhancement over control devices.

NOVEL CLUSTER-CARBON IMPLANT AND LASER ANNEAL TECHNOLOGY, AND DEVICE INTEGRATION

Key process steps for realizing the e-Si:C S/D stressors with the new cluster-C implant and laser annealing technology are illustrated in Fig. 1. After definition of active regions, well implant, threshold voltage V_t adjust implant, and anti-punchthrough implant were performed. Poly-Si/SiO_2 gate stack, S/D extension (SDE), and silicon nitride SiN spacers were then formed. For strained n-FET wafers, implantation of cluster-carbon or ClusterCarbon™ ($C_7H_7^+$) (effective C dose of 8×10^{15} cm^{-2}) into the S/D region was performed. For control n-FET wafers, Si PAI (1×10^{15} cm^{-2}) was performed. For fair comparison, S/D amorphization depths for all wafers were kept the same. A SiO_2 hardmask on the gate blocked the $C_7H_7^+$ or Si implant and also served as a protection layer to maintain gate stack integrity during subsequent PLA. As^+ implant (8×10^{14} cm^{-2} at 25 keV) and a rapid thermal anneal (RTA) of 950°C 30s were done to form deep S/D regions. This was followed by a higher dose but shallower As^+ S/D implant (2×10^{15} cm^{-2} at 15 keV) to improve the contact resistance of the non-silicided S/D regions. This As^+ implant also amorphizes the Si surface. A 30 nm thick SiO_2 layer was deposited to minimize carbon out-diffusion in a subsequent laser anneal as well as to function as an anti-reflective coating. Integration challenges such as melting of the gate associated with use of high laser fluence are avoided. Following laser anneal, SPE occurred in the C-containing regions to form the crystalline Si:C S/D stressors. Fig. 2 shows a transmission electron microscopy (TEM) image of an N-FET with Si:C S/D formed by $C_7H_7^+$ implant and laser anneal. Full restoration of the crystalline quality is observed in high resolution TEM images. Formation of high-quality Si:C in the S/D region is required for its application as stressors.

RESULTS AND DISCUSSION

A. New Cluster-Carbon Implant and Laser Anneal Technology

For cluster-C implant, $C_{14}H_{14}$ was used to produce the $C_7H_7^+$ ion beam. Main advantages of cluster-C implant include uniform C profile, high-throughput, low effective C energy, and ultra-high dose. Laser anneal data on C_{sub} optimization is shown in Fig. 3. High Resolution X-Ray Diffraction (HRXRD) is used to obtain C_{sub} in $C_7H_7^+$-implanted and laser annealed samples [7]-[8]. At an energy fluence of 375 mJ/cm^2, a C_{sub} of ~1.1% was obtained as illustrated in the HRXRD [Fig. 4(a)]. (004) and (224) reciprocal space maps obtained after PLA reveal a perfect alignment of the Si:C and Si intensity peaks indicating that lattice alignment along the heterojunction is maintained [Fig. 4(b) and (c)].

B. N-FETs with New Si:C S/D Technology

To ascertain the feasibility of forming Si:C S/D using Cluster-Carbon implant and PLA-induced SPE for strain engineering in n-FETs, we integrated both technologies in a standard n-FET process flow and performed a statistical comparison of the device performance. Slight reduction in junction leakage is observed for $C_7H_7^+$ implanted samples over Si PAI samples after PLA (Fig. 5). The slight reduction in junction leakage in the $C_7H_7^+$ implant samples could be due to reduced defect densities at the interface between amorphous and crystalline regions [9]. Fig. 6-7 show I_{DS}-V_{GS} and I_{DS}-V_{DS} plots for n-FETs with a gate length L_G of 100 nm. The smaller lattice constant of Si:C S/D induces uniaxial tensile strain in the Si channel. Hence n-FETs with Si:C S/D show a ~15% higher I_{DSAT} over unstrained control n-FETs. All n-FETs show comparable short channel effects and subthreshold characteristics. S/D series resistance for devices with Si:C S/D or Si S/D as obtained by examining the asymptotic behaviour of R_{TOTAL} curve at large V_G are comparable [Fig. 8]. The total resistance R_{TOTAL} as a function of L_G is shown in Fig. 9. An indication of enhanced mobility in the strained devices is shown by the smaller slope in R_{TOTAL}-L_G plot. The ratio of dR_{TOTAL}/dL_G of Si:C S/D devices over that of Si S/D devices indicates a mobility enhancement of 28%. Fig. 10 compares the I_{DSAT}-I_{OFF} plots of n-FETs with Si:C S/D and Si S/D at a fixed I_{OFF} of 100 nA/μm and shows an I_{DSAT} enhancement of 16% in the strained devices. In a comparison of I_{OFF} versus I_{DLin}, a higher enhancement of 26% is obtained for n-FETs with Si:C S/D [Fig. 11]. At a fixed DIBL of 150 mV/V [Fig. 12] and at a fixed subthreshold slope (SS) [Fig. 13] of 125 mV/decade, I_{DSAT} enhancement due to the Si:C S/D is 14% and 15%, respectively.

CONCLUSION

We demonstrated the first integration of a novel Cluster-Carbon ($C_7H_7^+$) and pulsed excimer laser-induced SPE technique to form embedded Si:C S/D stressors in nanoscale n-FETs. A substitutional carbon concentration of ~1.1% was obtained. N-FETs with Si:C S/D show a drive current enhancement of ~15% over control n-FETs and is attributed to strain-induced effects. Cluster-Carbon implant and anneal is a simple and attractive technique to integrate lattice-mismatched S/D stressors in advanced n-FETs and is a very promising option for future technologies.

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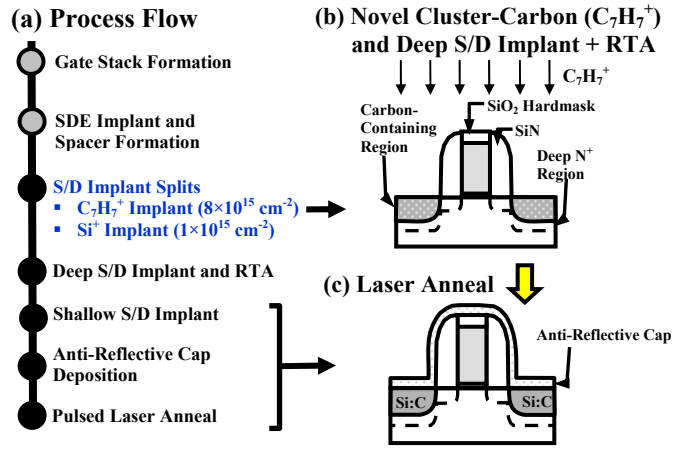

Fig. 1. (a) Key process steps employed in this work, including (b) cluster-carbon ($C_7H_7^+$) and arsenic As^+ implant, and laser anneal to form (c) n-FET with Si:C S/D stressors.

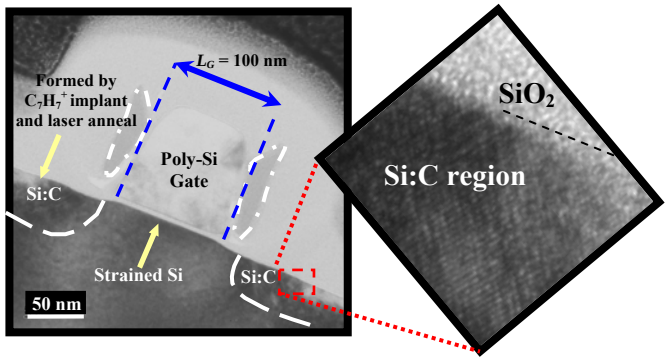

Fig. 2. TEM image of the n-FET having Si:C S/D with C_{sub} of 1.1%. After cluster-carbon implant and laser anneal, full restoration of the crystalline quality is achieved as seen in the HRTEM image.

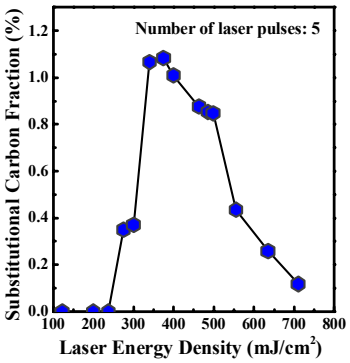

Fig. 3. Relation between C_{sub} and laser energy density. At 375 mJ/cm^2, C_{sub} of ~1.1% was obtained.

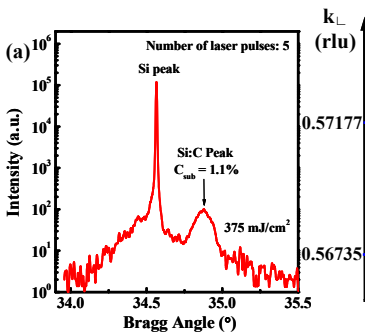

Fig. 4. (a) HRXRD plot indicates C_{sub} = 1.1% for a $C_7H_7^+$ implanted sample irradiated with 5 pulses of laser at 375 mJ/cm^2. Si:C is pseudomorphically grown on Si, as indicated by the (b) (004) and (c) (224) reciprocal space maps.

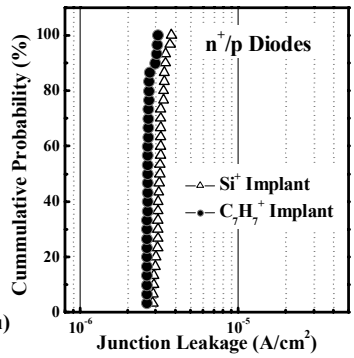

Fig. 5. Diodes that received $C_7H_7^+$ or Si^+ implant show comparable junction leakage current after laser anneal.

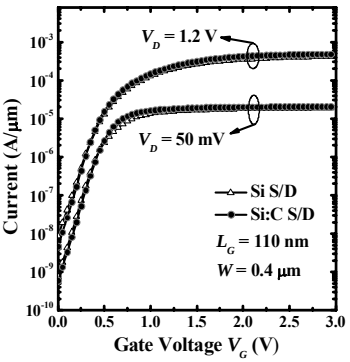

Fig. 6. I_{DS}-V_{GS} curves for n-FETs with Si:C or Si S/D showing comparable DIBL and subthreshold swing.

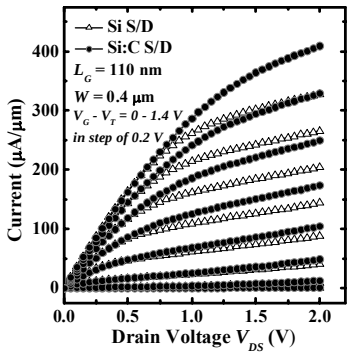

Fig. 7. Device with Si:C S/D shows significant enhancement in I_{DS} over devices with Si S/D.

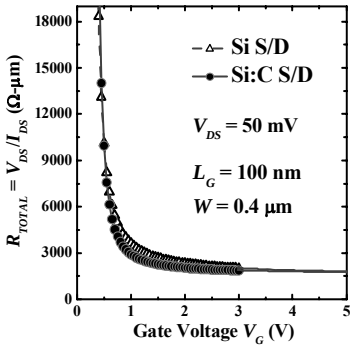

Fig. 8. S/D series resistance is comparable for n-FETs with Si:C S/D or Si S/D.

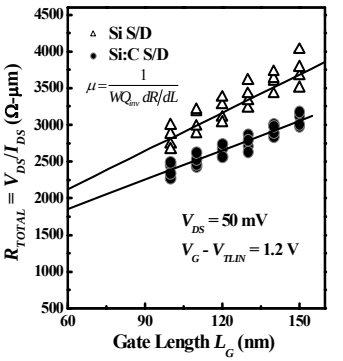

Fig. 9. Mobility enhancement due to Si:C S/D is ~28%, as indicated by the reduced dR_{TOTAL}/dL_G.

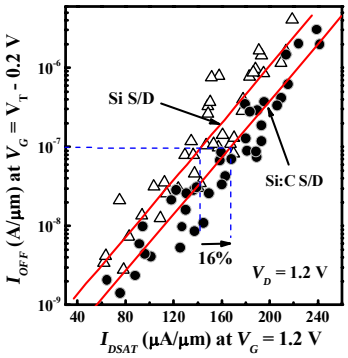

Fig. 10. 16% I_{DSAT} enhancement is observed for n-FET with Si:C S/D at I_{OFF} = 1×10^{-7} A/µm.

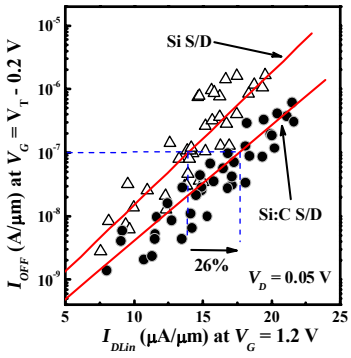

Fig. 11. At I_{OFF} = 1×10^{-7} A/µm, n-FET with Si:C S/D has 26% higher I_{Dlin} than the control n-FET.

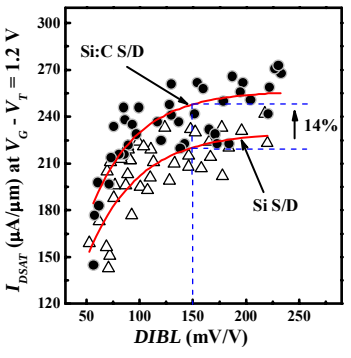

Fig. 12. At DIBL of 0.15 V/V, n-FET with Si:C S/D shows enhancement in I_{DSAT} of 14%.

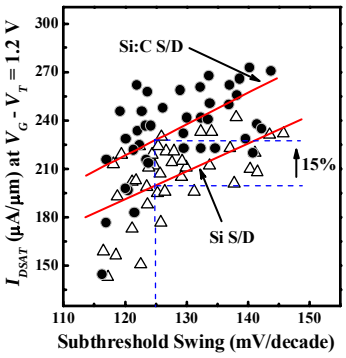

Fig. 13. At subthreshold swing of 125 mV/dec., n-FET with Si:C S/D demonstrates 15% higher I_{DSAT}.