S/D Contact Solutions to Enable Contact Resistivity <1E-9 for 5nm and Beyond

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ABSTRACT

In this paper, we present solutions for N&P MOS contact resistivity (ρc) improvement by adoption of highly doped epitaxial source/drain (S/D), contact ion implantation and advanced laser anneal. An ultra-low ρc = 9.01x10-10 Ω·cm2 on NMOS contact chain (CC) is achieved using highly doped (HD) Si:P selective epi in S/D combined with Ge PAI (pre-amorphization implant) and Applied Materials’ nanosecond laser anneal (NLA). In addition, a record low ρc = 1.16 x 10-10 Ω·cm2 for PMOS CC is demonstrated by Si0.5Ge0.45:B epi, Ga cryo implant and NLA. NLA enables super-activation of implanted dopants and dopants in the in-situ HD S/D epi films [(P): 3.0x10^21 cm^-3 for NSD epi; (B): 1.0x10^21 cm^-3 for PSD epi]. These new process technologies provide a pathway to achieve the target ρc required for transistor performance in advanced logic devices.

INTRODUCTION

Contact resistance is one of the key challenges that needs to be addressed as FinFET scaling for 10-7nm node [1, 2]. Recent work [3] reported by Yu et al showed that NMOS ρc of 1.5x10^-9 Ω·cm2 with a Ge PAI and AstraTM DSA anneal on HDSi:P (2x10^21 cm^-3). Additionally, conformal doping using PLAD and dynamic surface anneal (DSA) with better fin sidewall doping coverage for HDSi:P epi, resulted in low NMOS ρc of 1.2x10^-9 Ω·cm2 [4]. For PMOS, an optimized implant sequence resulted in low ρc of 2 x 10^-9 Ω·cm2 on Si0.5Ge0.45:B with Ti germanosilicidation [5]. Interestingly, in this reported study the first Ge PAI along with B implant followed by nanosecond laser anneal (NLA) enabled higher dopant incorporation and activation at the interface. Additional Ge PAI was performed before silicidation to form a high-quality silicide interface. Another recent study reported PMOS ρc of 1.9x10^-9 Ω·cm2 on group III element doped Ge with nanosecond laser annealing [6].

In this work, we report that optimizing the epi, implant and anneal techniques are paramount to reducing NMOS and PMOS ρc. We investigated the impact of Ge PAI with and without additional dopant implant, and compared different laser anneal techniques (millisecond laser anneal AstraTM DSA and NLA). Additionally, we reported the effect of dopant species (Ga vs. B) in SiGe:B, and evaluated the effect of activation achieved by AstraTM DSA vs. NLA.

EXPERIMENT

Process flows used for NMOS & PMOS CC ρc test vehicles are summarized in Figs. 1 and 2, with key process steps described below: HDSi:P epi (for NMOS) and Si0.5Ge0.45:B epi (for PMOS) were grown after STI/junction formation. After contact open, phosphorus or boron cryo (-100°C) implants for NMOS and PMOS were performed respectively, followed by laser anneal (DSA or NLA). Next, contact pre-clean (SiconiTM), contact liner (PVD Ti/ALD TiN) were applied, followed by silicidation anneal at 600°C spike, CVD W fill, and W CMP. The low ρc enabling processes (Si0.5Ge0.45:B epi, Ge, B and Ga implants, SiconiTM, and NLA) were done using Applied Materials proprietary tools. Device-equivalent CC test vehicle (Fig. 3) with contact CD’s ranging from 35-150nm was fabricated to evaluate ρc. By plotting CC resistance vs. diffusion length, ρc was extracted from the resistance values extrapolated to zero diffusion length, and normalized with contact CD’ (Fig. 3c). Detail of this method has been described in a previous publication [4].

RESULTS

Fig. 4 shows that optimal NLA conditions significantly reduce NMOS ρc to a record low 9.01x10^-10 Ω·cm². Highly P-doped epi with optimized ion implant is required for NMOS ρc reduction, as shown in Fig. 5. Ge PAI is a key step to form smooth and high-quality silicide interface; up to 53% reduction in ρc was achieved with Ge PAI vs. no Ge PAI (Fig. 6) after NLA. Fig. 7 is a TEM image of CC with Ge PAI before laser anneal, revealing a thick amorphous layer created by Ge PAI. The TEM image in Fig. 8 shows that this amorphous layer crystallized after NLA.

Fig. 9 compares different laser anneal techniques, DSA and NLA for B activation in Si0.5Ge0.45:B epi. It clearly shows that 67% improvement is achieved with NLA due to dopant super-activation and epi recrystallization. Fig. 10 shows PMOS ρc results for various ion implantation and NLA approaches. It is shown that ρc is reduced from 5.84x10^-10 to 1.16x10^-9 Ω·cm² by Ga I/I and NLA. Ion implantation into the contact provides high dopant concentration at interface and lowers the ρc. NLA enables super-activation of B in Si0.5Ge0.45:B epi film [7]. PMOS ρc results with and without Ga/B implants vs. NLA energy fluence are shown in Fig. 11. ρc decreases with increasing laser energy fluence and reaches a saturation level, indicating that at lower fluence, the amorphous layer begins to recrystallize, and it is fully converted to a crystalline layer at higher fluence. However, if the fluence is too high, it damages the contact hole and creates voids [7] that resulted in higher ρc. Fig. 12 shows STEM images of CC with either (a) low energy fluence or (b) high energy fluence. Higher fluence could melt the Si0.5Ge0.45:B epi film as shown in Fig. 12(b). Comparison of EELS results in Fig. 13 and Fig. 14 shows that NLA can cause Ge atoms to diffuse to Si/SiGe epi interface. The effective dopant activation in the Si0.5Ge0.45:B epi and contact interface is the dominant factors to reduce ρc.

CONCLUSIONS

We have successfully demonstrated advanced contact process techniques that provide pathways for NMOS and PMOS ρc improvement by integration of highly-doped epi films, cryo ion implantation and NLA super-activation. Optimization of implant and NLA conditions is critical for maximizing dopant activation, reducing defects and improving epitaxial regrowth, which resulted in low ρc. Ultra-low ρc values (9.01x10^-10 Ω·cm² for NMOS and 1.16x10^-9 Ω·cm² for PMOS) on CC were achieved in this work. The super-activated dopants by implantation and NLA allow promising pathway to enable N and PMOS ρc to below 1 x10^-9 Ω·cm².

REFERENCES

Figure 1. NMOS contact chain process flow on HDSiP Epi with P I/I splits and laser anneal for [P] activation.

Figure 2. PMOS contact chain process flow on SiGe: B epi with B or Ga I/I and DSA or nsec laser anneal.

Figure 3. (a) Contact chain structures (top view); (b) (cross-section) of schematic and SEM image.

Figure 4. NMOS $\rho_C$ as function of HDSiP dopant conc and NLA splits. All splits had Ge PAI. The P doping level varies from $1 \times 10^{21}$ to $3.5 \times 10^{21}$ atoms.cm$^{-3}$.

Figure 5. Pathway of NMOS $\rho_C$ reduction with S/D epi doping level and ion implant.

Figure 6. NMOS $\rho_C$ reduction as function of HDSiP dopant conc w/ and w/o Ge PAI splits post NLA. Up to 53% $\rho_C$ reduction was measured for HDSiP $(3.0 \times 10^{21}$ cm$^{-3}$) with Ge PAI and NLA.

Figure 7. XTEM of contact hole without anneal. A thick amorphous layer is formed between HDSiP epi and Ti metal.

Figure 8. XTEM of contact hole with optimal NLA. NLA transforms the amorphous layer into crystalline layer, resulting in lower $\rho_C$.

Figure 9. Comparison of DSA vs. NLA for B implanted SiGe:B.

Figure 10. PMOS $\rho_C$ vs. implant and anneal splits. $\rho_C$ is reduced from $5.84 \times 10^{-9}$ to $1.16 \times 10^{-9}$ $\Omega$·cm$^2$ by Ga I/I and NLA.

Figure 11. PMOS $\rho_C$ for I/I splits vs. nsec laser energy fluence. Up to 75% $\rho_C$ reduction is observed from $4.47 \times 10^{-9}$ to $1.16 \times 10^{-9}$ $\Omega$·cm$^2$.

Figure 12. STEM images of PMOS contact chain with NLA (a) low and (b) high fluence.

Figure 13. EELS results of low laser fluence indicate no Ge diffusion from epi film to Si.

Figure 14. EELS results of high laser fluence indicate Ge diffusion from epi film to Si which damages the contact.