Atomically Controlled Plasma CVD Processing for Quantum Heterointegration of Group IV Semiconductors

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A few nanometer-order ultrathin film deposition with atomically controlled interfaces is important to create quantum effect devices with Si-based group IV semiconductors [1,2] for heterointegration of new function on Si LSI. Plasma enhanced chemical vapor deposition (CVD) is expected to be useful to improve interface flatness and abruptness by lowering epitaxial growth temperature. In this paper, atomically controlled plasma processing of low-temperature epitaxial growth and doping of group IV semiconductor nanostructures without substrate heating is reviewed.

Atomically controlled surface reaction of reactant gases (SiH_4, B_2H_6, GeH_4 and N_2) for deposition was enhanced under low-energy Ar plasma irradiation without substrate heating. Especially to avoid plasma damage and intermixing, a low-energy Ar plasma condition with Ar pressure as high as a few Pa without substrate heating (**Fig. 1**) [3,4] is important to obtain a peak ion energy as low as a few eV or below and to maintain lower surface temperature below 100 ^{o}C during deposition.

Atomic-layer (AL) doping in group IV semiconductors is expected to introduce 2-dimensional lattice strain as well as high-concentration carriers to modulate electronic properties. AL doping of B and N has been examined by AL formation of B or N on Si(100) and Si cap layer deposition by reaction of B_2H_6 or N_2 and SiH_4, respectively, under Ar plasma irradiation [5,6]. It was found that, even without substrate heating, a Si cap layer can be epitaxially grown at an impurity atom amount as high as $7x10^{14}$ cm^{-2} and that most of the incorporated impurity atoms can be confined in a few nm-thick region (**Fig. 2**). It should be noted that, in the case with Si cap layer deposition B AL under higher energy plasma condition, a part of B atoms on Si(100) desorb due to Ar plasma irradiation. Therefore, a low-temperature and low-energy plasma processing is indispensable for heavy AL doping.

Formation of highly strained epitaxial heterostructures of Si, Ge and high-Ge-fraction $Si_{1-x}Ge_x$ alloy is essential for high-performance heterodevices with group IV semiconductors under suppression of misfit-dislocation generation and intermixing. By the reaction of GeH_4 under low-energy Ar plasma irradiation without substrate heating, a relaxed or highly strained Ge layer with atomic-order flatness can be epitaxially grown on Si(100) (**Fig. 3(a)**) [3]. Moreover, by using a thin 84%-relaxed Ge buffer layer on Si(100) (grown under higher-energy Ar plasma condition), it was found that an ultrathin undoped strained Si layer with atomic-order flatness can be epitaxially grown by the reaction of SiH_4 under low-energy Ar plasma irradiation without substrate heating [7]. Especially below 2 nm, the surface strain amount reaches above 3 % (**Fig. 3(b)**). Such an atomically controlled growth of highly strained nanometer-order thin films are based on the improved controllability of flatness, as well as strain, in the plasma CVD processing for the Ge and Si layers at low temperatures. These results promote development of atomically controlled plasma processing for group IV semiconductor heterointegration of quantum effect devices on Si LSI.

References

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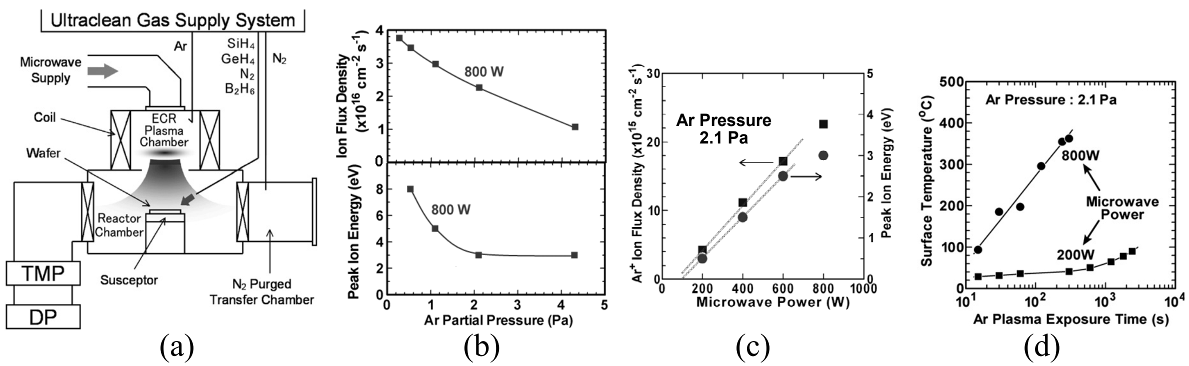

Fig. 1 (a) Schematic of ECR plasma CVD system. (b)(c) Ion flux density/peak ion energy and (d) surface temperature.

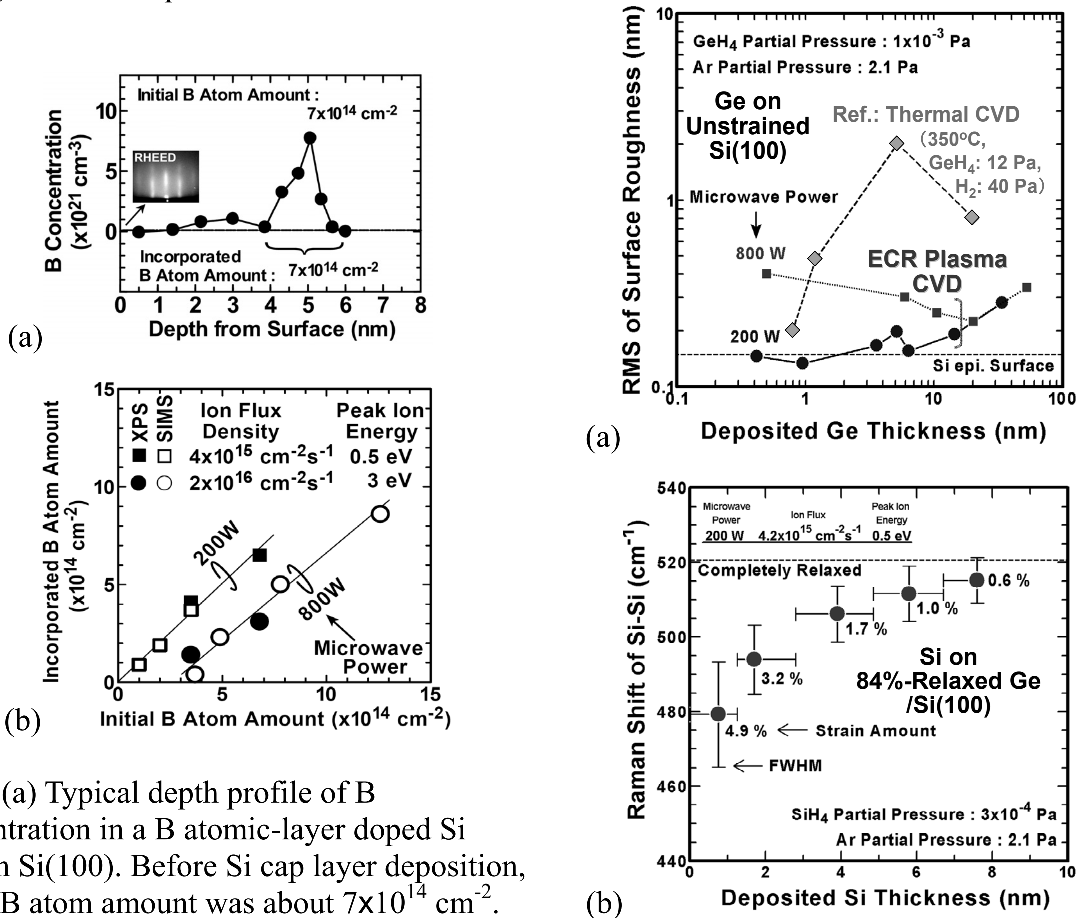

Fig. 2 (a) Typical depth profile of B concentration in a B atomic-layer doped Si film on Si(100). Before Si cap layer deposition, initial B atom amount was about 7x10^{14} cm^{-2}. (b) Relationship between initial B atom amount and incorporated B atom amount after Si cap layer deposition under the lower energy and higher energy plasma conditions.

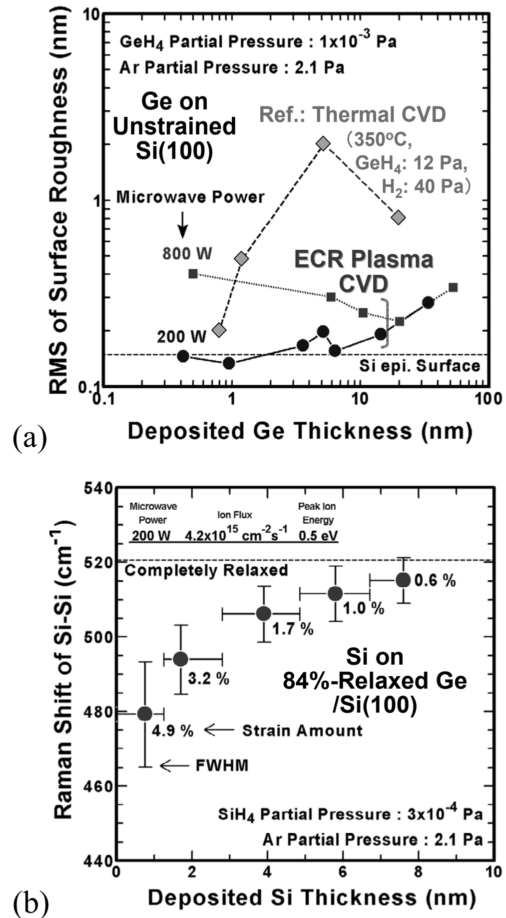

Fig. 3 (a) Surface roughness of Ge on unstrained Si(100) and (b) Raman shift of Si on 84%-relaxed Ge/Si(100).