Strain modification in thin $Si_{1-x-y}Ge_xC_y$ alloys on (100) Si for formation of high density and uniformly sized quantum dots

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The effects of alloying C with Ge and Si and varying the C/Ge ratio during the growth of very thin layers of the ternary alloy SiGeC grown on Si (100) substrates and the resulting strain modification on self-assembled and self-organized quantum dots are examined. During coherent islanded growth, where dislocations are not formed yet to relieve the strain, higher strain energy produced by greater lattice mismatch acts to reduce the island size, increase the density of islands, and significantly narrow the distribution of island sizes to nearly uniformly sized quantum dots. Strain energy can also control the critical thickness for dislocation generation within the three-dimensional islands, which then limits the maximum height which coherent islands can achieve. After the islands relax by misfit dislocations, the island sizes increase and the island size distribution becomes broader with the increase of misfit and strain. The optimal growth for a high density of uniform coherent islands occurred for the $Si_{0.49}Ge_{0.48}C_{0.03}$ alloy composition grown on (100) Si, at a growth temperature of 600 °C, with an average thickness of 5 nm, resulting in a narrow size distribution (about 42 nm diameter) and high density (about 2×10^{10} dots/cm^2) of quantum dots. [S0021-8979(99)00801-4]

I. INTRODUCTION

Since the advent of molecular beam epitaxy over two decades ago, the growth of semiconductors with monolayer control has attracted enormous attention for quantum confined semiconductor structures.[1–3] Low dimensional structures have generated tremendous interest at many levels including the study of their fundamental physics as well as potentially important technological applications in electronic and optoelectronic devices due to their new electronic and optical properties. Currently there has been a tremendous commercial success in applications of quantum well based devices.[4] Quantum wires and quantum dots have numerous advantages over quantum wells. For example, quantum dots allow single charge counting and tunneling,[5–7] and the higher confinement modifies the density-of-states to significantly lower laser threshold currents and elevate differential gain. The fabrication of quantum wires and quantum dots with high densities and high uniformity, however, is difficult. Some experimental methods require complex and expensive lithography and processing. An alternative approach is self-organization by directly controlling the two-dimensional (2D) to 3D growth transition induced by lattice misfit stress. Studies on the surface morphology of heteroepitaxial films showed that the growth kinetics are strongly influenced by lattice mismatch induced strain energy, surface free energy, growth temperature, and growth rate.[8–10]

SiGe alloys seem to be a promising material system for realizing quantum dot structures for terabyte storage applications, since they can readily be implemented within existing Si technology. The growth of Ge on Si follows the Stranski–Krastanov mode of self-organized Ge-island formation when the epilayer thickness exceeds a few monolayers.[11–16] The addition of small amounts of C to SiGe acts to compensate in approximately a 1:8 ratio the compressive strain created by

ferred into the growth chamber where they were prebaked at 200 °C following a procedure similar to that discussed in Eaglesham *et al.*[19] The prebake was shown to effectively desorb hydrocarbons on the Si surface which resulted in high quality Si epitaxy for substrate temperatures of $\geqslant$370 °C (defect densities $<10^5$ cm^{-2}). This step is necessary to avoid carbon contamination at the surface, which may act as nucleation sites for 3D growth. The samples were ramped to the growth temperature and the (2×1) reconstructed Si surface was confirmed by reflection high energy electron diffraction (RHEED). The substrate temperature during growth was held at 600 °C. The nominal film thickness for all the layers, assuming 2D growth, was 5 nm. Growth of the thin layers was performed without a buffer layer, but after RHEED confirmation of the $(2\times1$

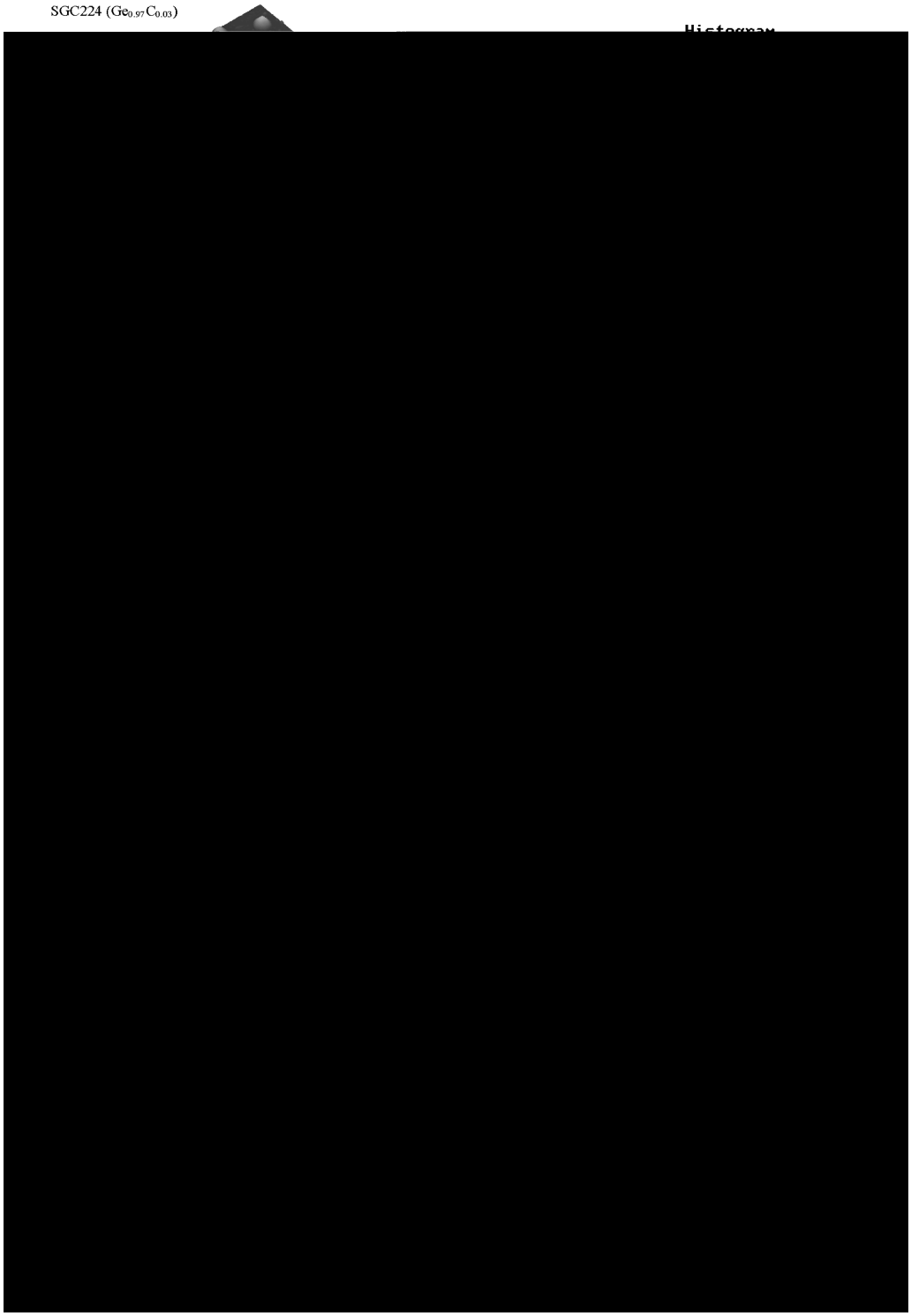

FIG. 1. AFM topographs of: (a) $Ge_{0.97}C_{0.03}$ (SGC224), (b) $Si_{0.39}Ge_{0.58}C_{0.03}$ (SGC225), (c) $Si_{0.49}Ge_{0.48}C_{0.03}$ (SGC226), and (d) $Si_{0.7}Ge_{0.27}C_{0.03}$ (SGC227), and their corresponding histograms, showing island size distribution. Insets show their corresponding postgrowth RHEED pattern.

seen from *in situ* reflection high-energy electron diffraction (RHEED), as shown in the insets in Figure 1.

Low temperature photoluminescence (PL) studies of all four layers are shown in Fig. 3. In all the layers a peak at 1.09 eV was observed which is related to the Si substrate. Narrow peaks are observed at 0.789 and 0.767 eV, as well as a broad band centered at 0.75 eV in the layers that contain silicon. They were found to increase in intensity with increasing Si content and decreasing Ge/C ratio. Very similar luminescence was observed by Wang *et al.*,[22] and was attributed to Ge no-phonon lines. However, studies of thermally induced defects in silicon by Minaev *et al.*[23] and Weber *et al.*[24] revealed luminescence at the same locations. They observed that electron–vibrational emission bands, *P* (0.767 eV), *H* (0.9258 eV), *T* (0.9356 eV) and *I* (0.9653 eV), found in *n*-type and *p*-type silicon caused thermally induced de-

fects, incorporating oxygen and carbon impurity atoms. Additionally, they found the *P* line increased in intensity when the oxygen concentration was substantially larger than the carbon concentration. We attribute these PL lines in the SiGeC layers to thermally induced defects. The reason may be due to the thermal limitations on the Si effusion cell used in this study. Due to the ceramic crucible used for the Si source, the Si furnace cannot be raised too high in temperature. As a result, the epitaxial growth rate drops off considerably with increasing Si content. As the growth rate is reduced, the likelihood of impurity incorporation increases. For this reason, the oxygen contamination climbs with increasing Si content, and probably deleteriously affects the growth front of the last sample (SGC227), which is expected to exhibit a layer-by-layer 2D growth front with only a 0.1% misfit.

IV. CONCLUSIONS

Our results show that during coherent islanded growth, a larger Ge content, and therefore greater strain, can reduce the island size, increase island density, and narrow the island size distribution. Strain can also control the critical thickness for dislocation generation within 3D islands, which limits the maximum height that coherent islands can achieve. After relaxation by misfit dislocations, the island size increases and the island size distribution becomes broader with the decrease of Si content and increase of strain. In our case, the optimal growth for a high density of uniform coherent islands occurred for the composition of $Si_{0.49}Ge_{0.48}C_{0.03}$ on (100) Si, at a growth temperature of 600 °C, for an average thickness of 5 nm, resulting in a narrow size distribution (about 42 nm diameter) and high density (about 2×10^{10} dots/cm^2).

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