

## Effects of CBr<sub>4</sub> in Growth of GeSn(C)

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**ABSTRACT.** This paper reports the growth and characterization of tensile strained Ge<sub>x</sub>Sn<sub>y</sub>C<sub>1-x-y</sub> epitaxy on GaAs substrates using hybrid molecular beam epitaxy (MBE). Carbon tetrabromide (CBr<sub>4</sub>) was used as the carbon source. High resolution x-ray diffraction (HRXRD) reveals good crystallinity in the epi-layer with maximum 3% of substitutional carbon and 3.9% tin. Raman spectroscopy showed Ge-C and Ge-Sn bonds. Unlike previous reports using CBr<sub>4</sub> or most other carbon sources, no sp<sup>2</sup> (graphitic) or amorphous carbon bonds were detected. AFM showed mostly flat surfaces with a maximum roughness of 0.54 nm. The successful incorporation of C into Ge substitutionally, without cluster carbon, is a major step toward efficient Group IV lasers.

**Keywords:** Silicon photonics, germanium, direct bandgap, Group IV lasers.

Alloying Ge with either ~10% Sn or ~1% C turns the material into a direct bandgap suitable for active silicon photonics. Non-equilibrium growth in MBE and local strain compensation can both overcome the low solubility limits of C and Sn. In this paper, we present the epitaxial growth of GeSnC with successful incorporation of >2% C and no detectable amorphous or graphitic C. All samples were grown in a hybrid MBE from 160 °C to 240 °C using solid source Ge and Sn, and CBr<sub>4</sub> as a gas source. The Ge<sub>1-x-y</sub>Sn<sub>x</sub>C<sub>y</sub> epilayer (~200 nm) was grown on a 150 nm Ge buffer layer on a GaAs substrate, which was deoxidized under atomic H in-situ.

Narrow, well-defined GeSnC peaks were observed in high resolution x-ray diffraction (HRXRD)  $2\theta$ - $\omega$  scans with clear and numerous Pendelösung fringes of the samples grown at these temperatures (Fig. 1a). The concentrations extracted from XRD peak positions were Sn (3.92%, 2.79%, 1.91%, 1.42%) and C (2.96%, 2.53%, 2.16%, 1.6%) at 160 °C, 180 °C, 200 °C and 220 °C, respectively. Absence of fringes and loss of tensile strain suggests 240 °C is too hot for GeSnC. Rocking curve scans demonstrated narrow peak width with FWHM as low as 42 sec at 180 °C, showing good crystal quality. A reciprocal space map (Fig. 1b) shows the GeSnC layer is coherently strained with the GaAs substrate.

Reflection high energy electron diffraction (RHEED), showed clear 2×2 reconstruction at 160-200 °C but became spotty at 220-240 °C, which may indicate 3D island growth (Fig. 2). Atomic force microscopy (AFM) similarly showed flat surfaces with maximum roughness of 0.54 nm for the samples grown at 160-200 °C. To analyze the impact of C in the GeSn lattice, three C-free GeSn samples were grown at the same specifications. The AFM result comparison between GeSnC and GeSn layers demonstrated relatively flat surface at 160c and 180c, but GeSn has islands compare to GeSnC layers (Fig 3). Therefore, it appears carbon improves GeSn surface quality, which we attribute to a reduction in local strain.

Raman signal intensity difference around the Ge-Sn mode (300 cm<sup>-1</sup>) would seem to suggest higher Sn incorporation at 240 °C and least incorporation occurs at 180 °C (Fig. 4a), but XRD shows otherwise. Since Raman counts both substitutional and interstitial elements and XRD counts only substitutional elements, it is possible that at 180 °C much of the Sn incorporation is substitutional. At other temperatures, the interstitial Sn may affect the incorporation of C into the lattice, so the Ge-C local mode (530 cm<sup>-1</sup>) is only seen at 180°C (Fig 4b). Followup XPS and RBS are underway and will be presented. Also, significantly, no sp<sup>2</sup> or carbon cluster peaks are present in the 1200-1600 cm<sup>-1</sup> range, suggesting the vast majority of carbon was incorporated substitutionally rather than graphitic or amorphous (Fig. 4c).

In summary, Sn and C both appear to help incorporation of the other in Ge-rich alloys. This opens the door for direct bandgap materials compatible with silicon.

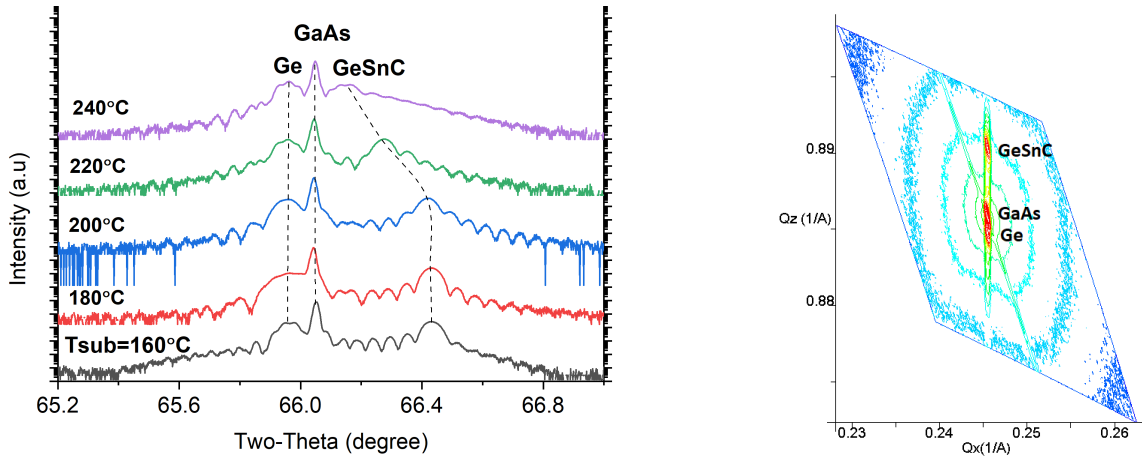


Fig. 1. (a) HR-XRD (004)  $2\theta$ - $\omega$  scan of GeSnC samples with various substrate temperature and (b) (115) XRD RSM of  $\sim$ 200nm GeSnC layer

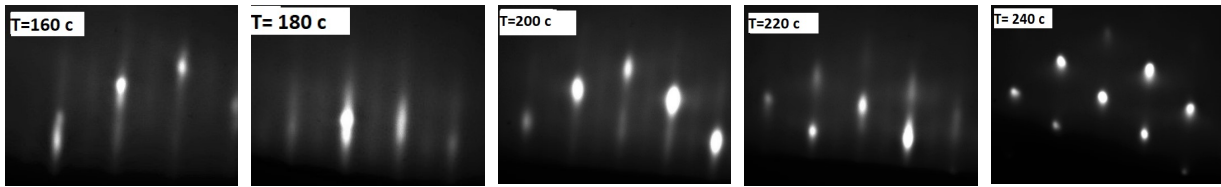


Fig. 2. RHEED pattern from GeSnC  $2\times 2$  reconstructed surfaces at various substrate temperatures ( $^{\circ}\text{C}$ )

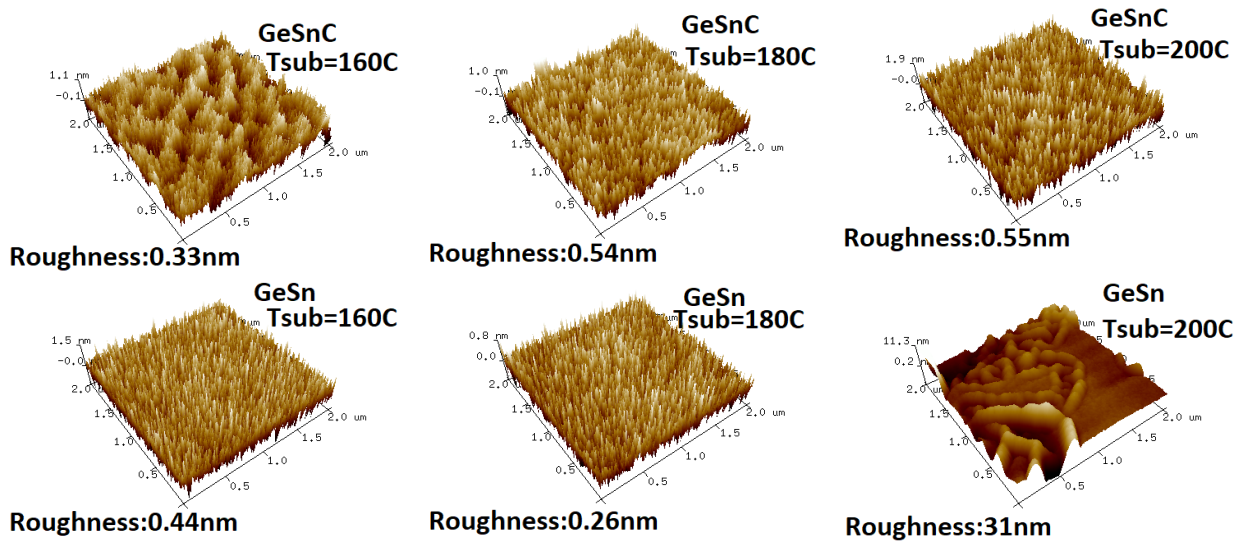


Fig. 3 Three dimensional illustration of AFM surface scans ( $2\times 2\ \mu\text{m}^2$ ) comparison for GeSnC and GeSn layers at various substrate temperatures

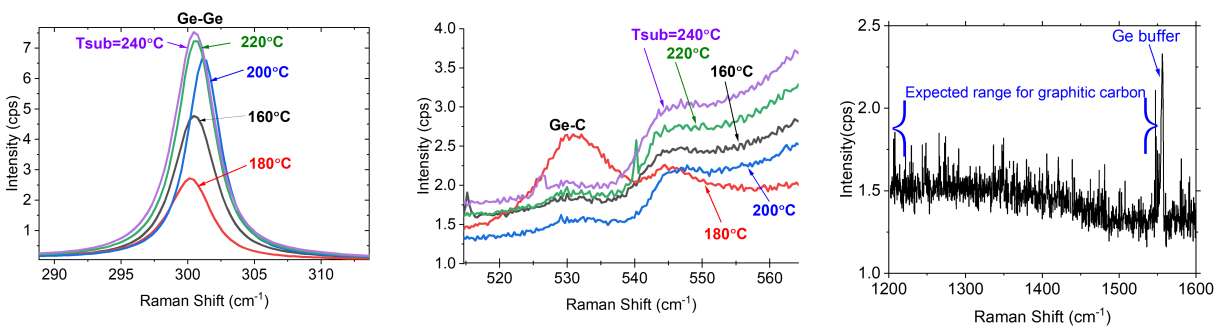


Fig. 4. Raman Spectra for GeSnC layer in (a) Ge-Sn, (b) Ge-C local mode and (c) amorphous carbon region