Low temperature growth of the epitaxial Ge layers on Si(100) by Hot Wire Chemical Vapor Deposition

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Abstract. In the present paper, we report on the growing of thick (≈0.2-3.0 μm) epitaxial Ge/Si(100) layers by Hot Wire Chemical Vapor Deposition (HWCVD) at low growth temperatures (350°C). The single crystal epitaxial Ge layers with low threading dislocation density (~10\textsuperscript{5} cm\textsuperscript{-2}) and surface roughness (< 0.5 nm) have been obtained.

1. Introduction
The possibility of heteroepitaxial growth of pure Ge on Si(100) substrates has generated a high interest because of the prospects for their potential applications in various novel electronic and photonic devices [1]. The high electron mobility, small direct bandgap of Ge (≈ 0.8 eV at room temperature), and the compatibility with well established silicon-based complimentary-symmetry metal-oxide-semiconductor (CMOS) technology makes it possible to design efficient photodetectors operating in the low optical fiber loss window (the light wavelength \(\lambda\) ranging from 1.3 to 1.55 μm) [2]. However, the key issue in growing the Ge films on Si for device applications is overcoming the negative effects of the large lattice mismatch (4.2% at 300K) between these two materials, which results in a high misfit dislocation density at the Ge/Si interface and a high threading dislocations density (TDD) in the Ge layers along with a high surface roughness due to island growth. To reduce the misfit dislocation density, various approaches have been proposed, e. g. a cyclic thermal annealing at the temperatures varied from 700 to 800°C and back [3]. However, for the integration of Ge/Si photodetectors into standard CMOS integrated circuits (ICs), low temperature growth techniques of the Ge layers are desired highly [4].

Hot Wire Chemical Vapour Deposition (HWCVD) is one of the promising candidates for the low-temperature Ge/Si heterostructure growth providing the abrupt heterointerfaces [5]. In this paper, we report on the growing of thick (up to 3 μm) single crystal epitaxial Ge layers on Si(100) using HWCVD method.
2. Experiment
The epitaxial growth of Ge films on Si(100) was carried out in a home made Ultra High Vacuum (UHV) system for Molecular Beam Epitaxy (MBE) of Si and Ge shown schematically in Figure 1. The base residual pressure in the growth chamber was less than $10^{-7}$ Torr.

![Figure 1. Schematic representation of HWCVD setup for the epitaxial growth of Ge layers on Si(100) substrates.](image)

The Ge layers were grown on n-Si(100) substrates (the specific resistivity of the substrate material was 4.5 and 0.005 $\Omega\cdot$cm) with an epiready grade polished (100) surface. The Si buffer layers were grown from a sublimation Si source at the substrate temperature $\approx 800^\circ$C. The deposition of Ge was carried out by letting purified germane ($\text{GeH}_4$) inside the growth chamber through a leak valve. Germane was cracked pyrolytically on a tantalum (Ta) filament located 3 cm away from the substrate. The filament was heated up to $1200 \div 1500^\circ$C by a direct electrical current. The filament temperature was measured by an optical pyrometer. The partial pressure of germane inside the growth chamber was $(1 \div 4) \cdot 10^{-4}$ Torr, the substrate temperature during the deposition of Ge was $\approx 350^\circ$C.

The surface morphology and roughness of deposited Ge films were examined by Atomic Force Microscopy (AFM). The crystal structure of the Ge films was examined by Double crystal X-Ray Diffraction (DXRD) and by Reflection Electron Diffraction. In addition, the elastic strain in the Ge/Si(100) epilayers was examined by Raman Spectroscopy. The threading dislocation density in the Ge/Si(100) films was determined by standard etch pit counting method. To study the depth profiles of the impurity concentrations in the Ge layers Secondary Ion Mass Spectrometry (SIMS) has been applied. The carrier concentration and mobility in the Ge/Si(001) films were measured by standard van-der-Pauw method at room temperature using the samples grown on low conductive substrates.

3. Results and discussion
The growth rate of the Ge layers was found to depend on the temperature of the Ta filament linearly (see Figure 2). Evidently, increasing the filament temperature increases the decomposition rate of germane. As a result, the Ge flux density onto the substrate increases with increasing Ta filament temperature.
The Ge growth rate (Å/sec) as a function of the Ta filament temperature.

The Reflection Electron Diffraction pattern of a Ge film on Si(100) demonstrated a typical single crystal diffraction pattern with Kikuchi lines expressed clearly (Figure 3) that points to the single crystal structure of the Ge film.

The dependence of the full width at half maximum (FWHM) of the Ge(004) peak in the X-ray diffraction curves of the Ge/Si(100) films on the Ta filament temperature is shown in Figure 4. It should be noted that the growth times for the Ge layers were the same for all samples, therefore, the higher the Ta filament temperature, the thicker the Ge layer.
The overall surface morphology pattern of the Ge/Si(100) layers surface was found to be a step(terrace)-wise pointing to two-dimensional layer-to-layer growth mode. The averaged root-mean-square (RMS) surface roughness of the Ge layers over a scan area of 2.5 mkm² was ≈ 0.37 nm that satisfies well the requirements of modern CMOS technology.

Raman spectroscopy (Figure 5) revealed a red shift of the Ge peak form the Ge/Si(100) epitaxial films (302.02 cm⁻¹) relative to the bulk Ge reference (300.7 cm⁻¹) indicating the tensile strain of the Ge layers.

The SIMS impurity depth profiles in the Ge/Si(100) films shown in Figure 6 demonstrate clearly that the carbon (12 C) and oxygen (16 O) concentrations in the epitaxial Ge film is lower than those in
the Si substrate. A considerably long decay tail of the Ge concentrations profile into the Si substrate could be attributed to the knock-in effect.

The treading dislocation density (TDD) in the Ge/Si(100) layers was ~ $10^5$ cm$^{-2}$. This value is among the lowest ones reported in the literature [6].

The Hall measurements performed on the samples grown on low conductive substrates revealed the Ge film material conductivity to be the p-type one. The hole concentration and mobility at room temperature were $(1 \div 3) \cdot 10^{17}$ cm$^{-3}$ and $\approx 900$ cm$^2$/V·sec, respectively that is close to the respective values for bulk Ge [7].

4. Conclusion
The results of the present studies demonstrate the capabilities of Hot Wire Chemical Vapor Deposition in low-temperature growing thick (up to 3 µm) single crystal epitaxial Ge films on Si(100) substrates featured by low threading dislocation density, low surface roughness, and good electrical parameters. Such Ge/Si(100) films are promising for various device application in microelectronics and photonics, particularly, for the infrared photodetectors integrated into the Si-based CMOS ICs.

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