

Thickness effect on the structural and electrical properties of poly-SiGe films



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ABSTRACT

As lateral dimensions of electromechanical devices are scaled down to length scales comparable to electron mean free paths, the influence of thickness effect on their properties becomes *sine qua non*. This paper presents a detailed study of thickness effect on the Young's modulus, residual stress, resistivity and Hall mobility of ultrathin poly-Si₁₁Ge₈₉ films deposited by low pressure chemical vapour deposition. The Young's moduli for the films thicker than ~40 nm are close to the bulk value (135 GPa) while those of the thinner films are much lower. The reduction in resistivity and subsequent improved Hall mobility as thickness increases are discussed in light of surface morphology which is evident from atomic microscopy images. The near constant values of Young's modulus, resistivity and Hall mobility for the films thicker than ~40 nm are attributed to the columnar grain structure as confirmed by the transmission electron microscopy images.

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1. Introduction

Applications of polycrystalline silicon germanium (poly-SiGe) films have been successfully demonstrated in various technological devices such as low frequency comb drives, high frequency resonators, bolometers, gyroscopes and micromirrors among others [1]. The growing interest in poly-SiGe can be attributed to its low thermal budget (~450 °C) which has proven useful when monolithically integrating Micro/Nano-ElectroMechanical System (M/NEMS) with its driving electronic components in the MEMS-last approach [2]. The structural components of the above mentioned devices are fabricated with micrometer thick poly-SiGe films making surface effect irrelevant to their operational performances. However, as the need for device miniaturization becomes essential, knowledge of size dependent properties becomes *sine qua non*. Miniaturization leads to portable and compact devices which ultimately consume less power. In addition, miniaturized devices have high mechanical resonance frequencies and higher quality factors that are important for surface based sensing and detection [2–4].

Generally, properties of ultrathin films differ from their bulk counterparts due to enhanced surface-to-volume ratio. Also, these properties are influenced when the structural dimensions are scaled down to a length scale that is comparable to the electron mean free paths [5–7]. In literature, a few studies on mechanical, structural and electrical properties of poly-SiGe films have been reported [1,8,9]. However, a detailed study of how these properties change with thickness at nanoscale level is missing. Because miniaturized devices, such as nanoresonators, nanoswitches and biosensors among others, require the structural layers to be thinner than 100 nm, it is evident that a study of this type is important. This paper discusses the influence of thickness effect on some properties of ultrathin poly-SiGe films. To quantify this influence, we deposited and characterized films of various thicknesses ranging from ~18 to ~200 nm.

2. Experimental techniques

Poly-SiGe films were deposited on SiO₂/Si(1 0 0) substrate using an Applied Materials Centura low pressure chemical vapour deposition (LPCVD) system. The films were deposited by a thermal decomposition of pure silane (flow rate of 8 sccm) and germane (10% in hydrogen, flow rate of 180 sccm) at a heater temperature of 415 °C and a pressure of 60 Torr. These deposition conditions were selected by optimization as reported in our previous study [10]. Films of different thicknesses were deposited by varying the

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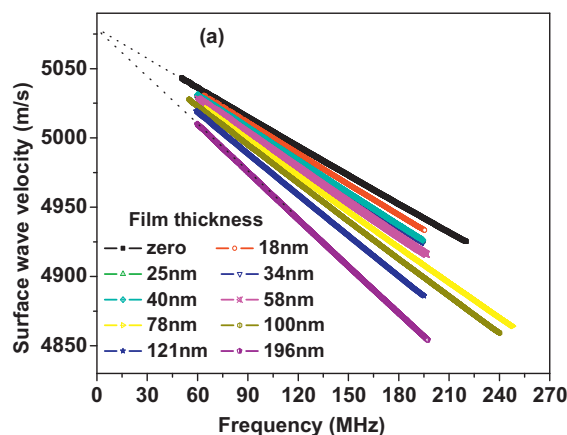
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deposition time. They were characterized by Scanning Electron Microscopy (SEM, FEI Nova 200), stress measurement (Frontier Semiconductor, FSM 128L), Atomic Force Microscopy (AFM, Multimode Digital Instrument), X-Ray Diffractometry (XRD, PANalytical X'Pert PRO MRD operating in 2θ - ω mode) and High Resolution Transmission Electron Microscopy (HRTEM, Tecnai F30, operating at 300 kV). Using Rutherford Backscattered Spectroscopy (RBS) and Secondary Ion Mass Spectroscopy (SIMS), we measured the germanium fraction and the boron concentration to be $\sim 89\%$ and $3.47 \times 10^{21} \text{ cm}^{-3}$, respectively.

The sheet resistance was measured with four-point probe (KLA-Tencor OmniMap RS75) while the Hall mobility and carrier concentration were determined by Hall Effect measurement (Keithley Instruments GmbH). The OmniMap RS75 probe contains 4 thin collinearly placed tungsten carbide probes which directly contact the sample under test [11,12]. A current (I) was applied to the outer electrodes and the voltage (V) across the inner electrodes was measured. The sheet resistance (R_s) was calculated from $R_s = k(V/I)$ where the geometric factor k for a circular sample is 4.53 [11]. A total of 49 points were measured for each film and the film resistivity was calculated from the average value. In Hall Effects measurement, samples of dimension $1 \text{ cm} \times 1 \text{ cm}$ were prepared and 4 contacts were made at the corners of these samples. The contacts contained indium oxide powders oven-backed at 380°C for 1 min. Measurements were done following the van der Pauw technique [13,14]. For each magnetic field (B), a constant current (I) was forced through two opposing contacts while Hall voltage (V_H) was measured across the other two. The magnitude of V_H is related to I , B and the carrier density N_s by: $|V_H| = IB/qN_s$. Based on the carrier concentration $N (=N_s \times h)$, the carrier mobility μ was calculated from: $\mu = 1/qN\rho$ where ρ , q and h are the resistivity, carrier charge ($1.602 \times 10^{-19} \text{ C}$) and thickness, respectively.

The Young's moduli were obtained by using surface acoustic wave (SAW) technique. According to Ref. [15] and some of the references therein, SAW is considered accurate and reliable for characterizing Young's moduli of ultrathin films. In SAW experiment, a nitrogen laser with pulse duration of 3 ns and a wavelength of 337 nm was used to generate wide band surface wave pulses. The surface acoustic waveforms were detected at different distances (say x_1 and x_2) across the sample. By taking the Fourier transformation of the waveforms, the frequency-dependent phase spectra, $\Phi_1(f)$ and $\Phi_2(f)$, were obtained. Subsequently, the phase velocity $c(f)$ was calculated from the dispersion equation (Eq. (1)).

$$c(f) = \frac{(x_2 - x_1)2\pi f}{\Phi_2(f) - \Phi_1(f)} \quad (1)$$



Following the procedure discussed in Ref. [15], the Young's moduli were estimated by minimizing the least square error between the measured curves and the theoretical data computed from the dispersion relation (Eq. (2)):

$$\sum_k [c(f_k) - c(E, E', \nu, \nu', \rho, \rho', kh, f_k)]^2 \quad (2)$$

where E , ν and ρ are the modulus, Poisson ratio and density of the substrate, respectively. The prime denotes film properties, k is the wave vector and h is the film thickness.

Following surface micromachining technique [10,16], we fabricated nanocantilevers from $\sim 55 \text{ nm}$ and $\sim 98 \text{ nm}$ thick poly-SiGe films and showed that the Young's modulus does not change significantly for films thicker than 40 nm. This was done by measuring the deflections at the tips of the released cantilevers from both SEM and AFM images. Based on the classical mechanics approach, we find that the deflection ratio does not differ substantially from the ratio of the thicknesses which confirms a similar Young's modulus.

3. Results and discussion

The evolutionary study shows that the Young's modulus of poly-SiGe film is influenced by size effect. According to Fig. 1(a), the changes in the slopes of the dispersion curves indicate slight changes in the Young's moduli as film thickens. In addition, the velocity of the silicon substrate in $(0\ 1\ 1)$ direction (5082 m/s) and the elastic constant C_{11} (165 GPa) are calculated by extrapolating the dispersion curves to the zero point, $f = 0 \text{ MHz}$. These values are used for subsequent calculation of the Young's moduli. Both the Young's modulus and the residual stress evolve following a similar trend (Fig. 1b). The Young's modulus is $\sim 113 \text{ GPa}$ at $h = \sim 18 \text{ nm}$ and increases gradually to $\sim 130 \text{ GPa}$ at $h = \sim 40 \text{ nm}$. For $h > 40 \text{ nm}$, it is evident that the moduli are fairly constant but slightly lower than the theoretical bulk value of 135 GPa. The dotted line represents the theoretical value for poly-Si₁₁Ge₈₉ film calculated from $E_{\text{Si}_{1-x}\text{Ge}_x} = 173 - 41x$ by taking $E_{\text{poly-Si}} = 173 \text{ GPa}$, $E_{\text{poly-Ge}} = 132 \text{ GPa}$ [17] and assuming $E_{\text{Si}_{1-x}\text{Ge}_x}$ is linearly related to x . A similar study relating germanium fraction to the modulus of SiGe is reported elsewhere [18]. The slight difference between the theoretical and measured values may be due to the measurement orientation. Depending on the film dominant orientation, smaller or higher values might be obtained [19]. However, the softening trend is observed for $h < 40 \text{ nm}$ where the Young's modulus decreases with thickness.

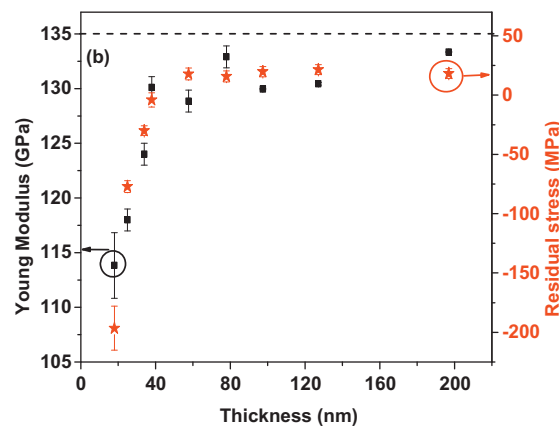


Fig. 1. (a) Dispersion curves. (b) Young's Modulus and residual stress versus film thickness for poly-SiGe films. The dash line is the theoretical Young's modulus for poly-Si₁₁Ge₈₉ films.

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