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Investigations of root strengthening in thermal treated $Si_{0.80}Ge_{0.20}$ and $Si_{0.75}Ge_{0.25}$ films

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ABSTRACT

We successfully discover the trend of elastic to plastic contact phenomena of 200-nm-thick $Si_{0.80}Ge_{0.20}$ and $Si_{0.75}Ge_{0.25}$ films using scanning probe microscope. It is evidenced that elastic to plastic contact is dominated using thermal treatment, based on a slightly machined track at 2000 μN. The sliding lines of samples at 800 and 900 °C tend to obtain slight penetration because elastic recovery and the sample at 1000 °C is mainly plastic deformation. In addition, it obviously mentions μ decreases while volume removed ratio is decreases and wear resistance increases at raised temperature. It implies that the relaxing of SiGe films protected against wear damage since the heavy concentrations of Ge elements to trap around the SiGe films. The root strengthen effect can be related to Ge elements induced from interdiffusion of the SiGe films. The role of elastic to plastic contact occurrence depends on the thermal treatment are evidenced.

1. Introduction

One of the important materials of semiconductor is silicon-germanium (SiGe) because of its attractive characteristics compared to silicon [1]. Potential application of the high-mobility strained SiGe-on-Si with high Ge–content is an effective channel material in metal oxide semiconductor [2]. However, 4% lattice mismatch of Si and Ge is occurred on SiGe/Si that remains a challenge owing to misfit dislocation formation above the critical thickness [3]. Strain relaxation cased both misfit dislocations and threading dislocations came from interfaces [4], can alter, therefore decaying the reliability of device applications [5]. In usual, the thermoelectric contributions of SiGe is focused, which helps to introduce a large density of dislocations and stacking faults, but less report focuses on the elastic/plastic transition using sliding contacts. As regards crystal solid, wear technique is employs to characterize abrasion resistance and adhesion strength of SiGe films. Because efficiency procedures to obtain qualitative elastic/plastic transition, scratch test involves the dynamic motion of a diamond indenter over the coated surface, therefore, is unique technique. The indenter test has been shown to be capable of capturing feasible characters, such as, hardness, Young's modulus, and coefficient of friction of SiGe [6–8]. Therefore, *in situ* captures of plied-up and critical failures from nano-tip are suitable investigation of SiGe films [9–11]. Scanning probe microscope (SPM)-based single abrasion is particularly important for the reliability assurance of thin films that has been employed in modification of surface at nanometer scale and fabrication of micro/nano structures [12]. Normally, SPM tip induce artificial damage was so-called scratch or wear [13,14]. It concluded that the resultant interfacial adhesion mechanism using such a convenient tool of scratch method [15,16]. The method is achieved that interactions between surfaces and more specifically the removal from deformation of material on a surface. Elastic/plastic response at the critical load depends on Archard's wear equation [17] is attributed as a result of the mechanical action from opposite surface.

The intention in this work was to apply Archard's wear equation; the volume removed was calculated during the course of scratching of the films using SPM. We apply SPM function to find the field of thermal treatment that can induces the elastic to plastic response of SiGe films. Understanding the abrasion damage is beneficial to the prevention of losses resulting from the SiGe surface.

2. Experimental details

Specimens were cleaned using a standard Radio Corporation of American (RCA) clean and washing for 15 s in a HF:H_2O (1:50) bath; the p-type Si(1 0 0) wafers were translated into the

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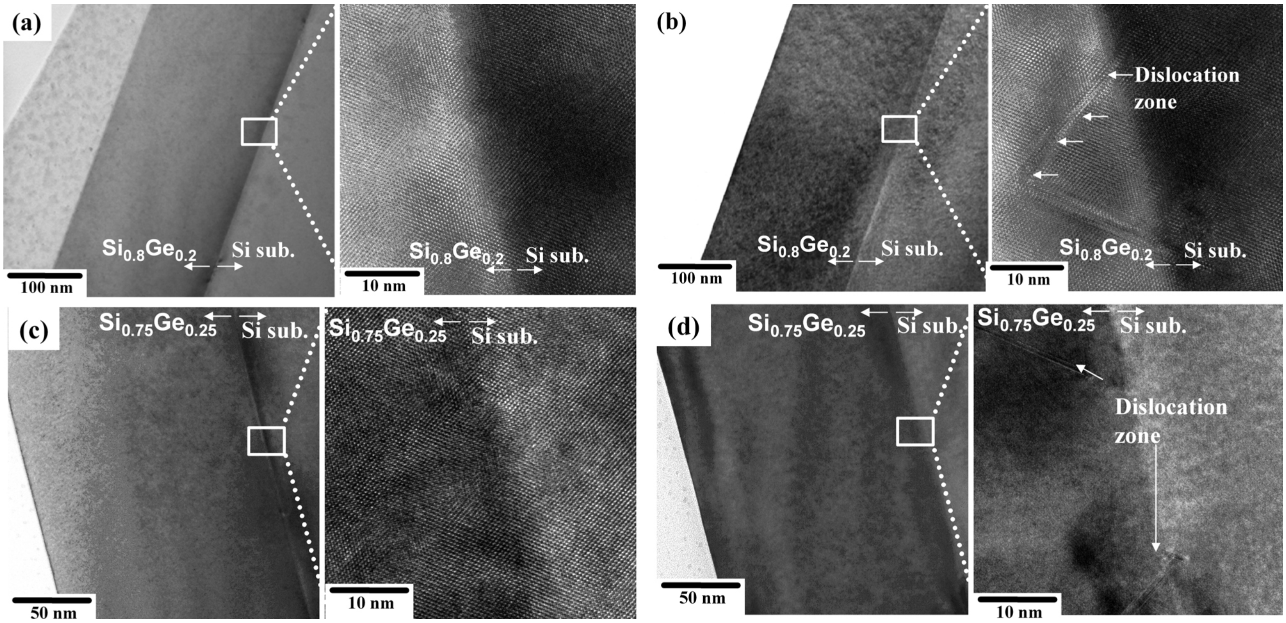

Fig. 1. Cross-sectional TEM images of $Si_{0.80}Ge_{0.20}$/Si substrate (a) without annealing and subjected to thermal treatment at (b) 1000 °C and $Si_{0.75}Ge_{0.25}$/Si substrate, (c) without annealing and subjected to thermal treatment at (d) 1000 °C, insert images are subjected in the interface of SiGe/Si substrate.

load-lock chamber of the ultra-high vacuum chemical vapor deposition (UHV-CVD) system. The deposition process involved three steps: (i) a 3-nm-thick Si buffer layer was deposited on the Si substrate at 500 °C for 30 min from pure SiH_4 (in 85 sccm) gas at a rate of deposition of 0.1 nm/min; (ii) a 200-nm-thick $Si_{0.80}Ge_{0.20}$ epilayer was deposited at 500 °C for 70 min from a mixture of pure SiH_4 (in 85 sccm) and GeH_4 (in 15 sccm) at a rate of deposition of 2.8 nm/min under a vacuum of 10^{-7} mbarr; (iii) a 200-nm-thick $Si_{0.75}Ge_{0.25}$ epilayer was deposited at 500 °C for 70 min from a mixture of pure SiH_4 (in 80 sccm) and GeH_4 (in 20 sccm) at a rate of deposition of 2.8 nm/min under a vacuum of 10^{-7} mbarr; both structures of (ii) $Si_{0.80}Ge_{0.20}$ and (iii) $Si_{0.75}Ge_{0.25}$ epilayer were completed after step (i) and the total thickness was ca. 200 nm; (v) both structures of SiGe films were subjected to thermal treatment (800, 900, and 1000 °C) *ex situ* in a furnace under N_2 gas for 30 min. The sample is without thermal treatment and at room temperature is so-called RT. The details of the UHV-CVD growth process of such samples have been reported elsewhere [11]. Morphology, elements distribution, and microstructure structure of the SiGe films were observed by means of scanning electron microscopy (SEM, Hitachi S-4000), energy-dispersive X-ray spectroscopy (EDS) mapping technique, and transmission electron microscopy (TEM, JEOL, JEM-2100F), respectively. In order to identify the wear abrasion performance of the samples, an atomic force microscope (AFM, Digital Instruments Nanoscope III) and a nanoindentation measurement system (Hysitron) were used to perform the scanning probe microscopy (SPM) mode, in which a constant normal load (F_n) of 2000 μN was applied at a constant scan speed of 1 $\mu m\, s^{-1}$ to those specimens. Surface profiles before and after scratching were obtained through tip-scanning at a normal load of 2000 μN. After scratching, the wear tracks were imaged by the *ex situ* SPM system. The cross-sectional scratch profile was scanned by the same tip of Berkovich indenter. In addition, from Bhushan [15], they define F_n and F_s as the normal force and the lateral force encountered in scratching, respectively. We obtain three tribological characteristics: (i) coefficient of friction (μ), (ii) wear coefficient (K), and (iii) wear resistance (R_w) that detail reported from literature [16].

$$\mu = F_s/F_n \tag{1}$$

We choose the Archard's wear equation [17], the volume removed during the course of scratching, V_w, is related to the dimensionless K in the following form:

$$V_w = K(S \times F_n)/H \tag{2}$$

where S is the total sliding distance and H is the hardness of the material. This equation suggests that V_w is proportional to S and F_n, while it is inversely proportional to H. Normally, K ranges are separated from different kind of material [18]. In Eq. (2), R_w in the unit of stress is defined by Rabinowicz et al. [19].

$$R_w = H/K = (S \times F_n)/V_w \tag{3}$$

For the SiGe films the K is given as 0.05. The average hardness (H) based on nanoindentation are 14.5 ± 0.6, 15.0 ± 0.6, 16.1 ± 0.4, and 16.2 ± 0.5 GPa; while SiGe films at RT and annealed at the temperatures of 800, 900, and 1000 °C [7].

3. Results and discussion

The restricted dislocations are produced around thermal energy of SiGe films, however, not yet study in detail at critical thickness of 200 nm. We employ TEM to character the cross-sectional $Si_{0.80}Ge_{0.20}$ films. In those observations, there is minimum defect at RT (Fig. 1a). However, numbers of defects at the interface of SiGe/Si substrate are found at thermal treatment of 1000 °C (Fig. 1b). We can compare that the cross-sectional $Si_{0.75}Ge_{0.25}$ films have similar condition, for the minimum defect at RT and propagation of dislocations are found at thermal treatment (1000 °C) as well (Fig. 1c and d). The SiGe film is enough to accept thermal budge at 1000 °C thus induce Ge elements to trap around the interface of Si substrate [20,21]. Fig. 2 reveals the results of EDS mapping that are analyzed on the cross-sectional $Si_{0.80}Ge_{0.20}$/Si substrate, where (a) is the $Si_{0.80}Ge_{0.20}$ films at RT, and (b) is at 1000 °C. The heavy concentrations of Ge elements are observed to trap around the interface of $Si_{0.80}Ge_{0.20}$/Si substrate at 1000 °C. Certain of Ge elements are transited into the surface of Si layer than did at RT. Bo et al. [6] have reported that a case of interdiffusion in the $Si_{0.80}Ge_{0.20}$ films (500 nm) corresponds to the supporting of the energetically thermal motion at the temperature of 500 °C. We agreed that suitable annealing temperature acts a role in promoting the interdiffusion