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An investigation of the effects of radiation exposure on stability constraints in epitaxial SiGe strained layers

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Abstract

The thermodynamic stability of device-relevant epitaxial SiGe strained layers under proton irradiation is investigated using X-ray diffraction techniques, and compared with its stability constrain under high-temperature annealing. Irradiation with 63 MeV protons is found to introduce no significant microdefects into the SiGe thin films, regardless of starting stability condition of the SiGe film, and thus does not appear to be an issue for the use of SiGe HBT technology in emerging space systems. The strain relaxation of SiGe thin film under thermal annealing, however, is sensitive to the composition and thickness of the as-grown samples, as expected, with the subsequent lattice relaxation of the unstable samples occurring at a much higher rate than that of metastable samples.

Keywords: SiGe; SiGe HBT; Thin film; Epitaxy; Stability; XRD; Radiation

1. Introduction

Epitaxially-grown SiGe strained layers have found wide application in Si-based bandgap engineering, and have been successfully applied to both HBTs [1], CMOS [2], and optoelectronic devices. Because Si and Ge are not lattice-matched (there is a 4% difference in lattice constant), SiGe alloys of perfect crystallinity are necessarily under compressive strain when grown on Si substrates. In SiGe HBT fabrication, the SiGe base layer is routinely used to increase β, decrease R_B, increase V_A, reduce noise, and increase f_T, leading to remarkable performance levels for fully-Si-processing-compatible technology ($f_T > 300$ GHz). SiGe films used in SiGe HBTs actually have a three-layer composite structure: a thin, undoped Si buffer starting layer; the actual boron-doped SiGe active base layer; and a thin, undoped Si cap ending layer. SiGe HBTs have been demonstrated to be inherently tolerant to ionizing radiation, thus potentially opening the door to a host of space-borne applications of SiGe devices [3]. A fundamental materials issue in SiGe technology remains unanswered, however, for the intrinsic SiGe base layer: How and to what level is the SiGe thin film stability affected by radiation? The present work uses X-ray diffraction techniques to investigate the impact of space-relevant proton irradiation on the material quality of epitaxial SiGe thin films suitable for use in SiGe HBT

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design, and examines three different Ge profiles spanning a range of thermodynamic stability (from thermodynamically stable to unstable). We also present the first comparison of the effects of proton irradiation and thermal annealing on stability in such SiGe thin films.

2. SiGe thin film stability

The SiGe base layer thickness is a key variable in SiGe HBT device design. The "critical thickness" is defined as the maximum film thickness for obtaining pseudomorphic (defect free) growth post-fabrication. Force-balance [4] and energy minimization [5] are the two most common approaches to theoretically determine the equilibrium critical thickness of a coherently strained layer. A recent equilibrium model for buried SiGe strained layers has been introduced and shows excellent agreement between theory and experiment from both CVD and MBE grown device-relevant SiGe films. This formalism employs force-balance theory and adds a proper consideration for the effects of the top Si cap layer on the total strain in the composite structure [6]. Theory predicts that during strained layer epitaxial growth the formation and glide (movement) of a network of misfit dislocations at the substrate/strained layer interface becomes energetically favorable when the thickness exceeds the film critical thickness. It is, however, generally agreed that SiGe films can be grown by certain low-temperature techniques to thicknesses exceeding the theoretical critical thickness (i.e., metastable) without creating misfit dislocations, provided processing conditions post-growth do not exceed the film growth temperature (550 °C for ultrahigh-vacuum/chemical vapor deposition (UHV/CVD)). As such, SiGe thin films can in principle be grown to several times the theoretical critical thickness (unstable) without lattice relaxation [7]. Since routine SiGe device and circuit fabrication includes several unavoidable high-temperature steps (e.g., oxidation and annealing in the range of 900 °C), SiGe strained layers which are metastable or unstable as-grown, however, "relax" (forming defects) during the subsequent device fabrication steps. Stable, metastable, and unstable SiGe thin films were fabricated by UHV/CVD, as shown in Fig. 1, and analyzed by X-ray diffraction both before and after exposure to 63 MeV protons. The impact of radiation on these SiGe thin films was further compared with thermal annealing effects.

3. Experiment

The SiGe thin films were grown on Si (100) by the UHV/CVD technique with exactly the same growth condition as that used in practical SiGe HBT fabrication [8]. Three experimental points in stability space were grown, which for clarity, we term "stable," "metastable," and "unstable", as shown in Fig. 1. The Si bottom buffer layer and cap layer thickness were fixed at 30 nm for all films. Ge "box" (constant Ge) profiles were used for ease of comparison. TEM cross-sections were made using standard mechanical "pre-thinning" (10–12 μm thickness) and subsequent formation

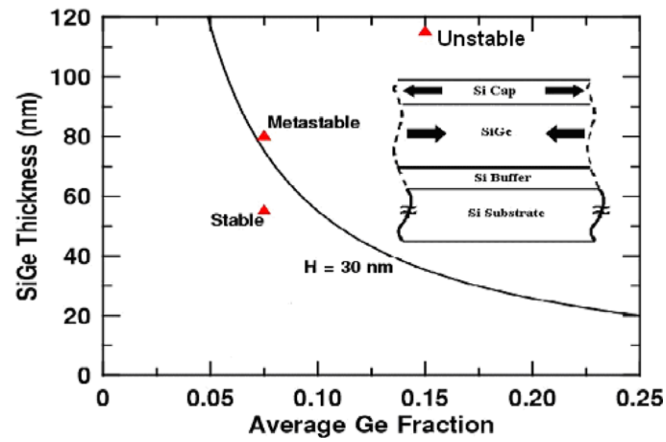

Fig. 1. SiGe thermodynamic stability diagram showing the stability points of the SiGe profiles used in this work. The solid line is a theoretical stability constraint curve. The inset shows the typical three-layer base structure of a SiGe HBT. The arrows indicates that SiGe layer is in compression while Si cap layer is in tension for a pseudomorphic structure.

of an approximately 15 μm wide by approximately 150 nm thick TEM membrane using a focused-ion beam-based (FIB) tool. X-ray diffraction (XRD) can be used to examine in great detail the underlying crystallinity of the films, and to infer the inherent strain present in the films. XRD measurements were carried out with a Philips materials research diffractor meter equipped with a rotating Cu anode X-ray source and a Hybird mirror/4 bounce monochromator indicent optics module. The reciprocal lattice map was obtained by undertaking a series of scans by driving the $2\omega'$ ($=2\theta$) and ω axes in a 2:1 ratio and then offsetting ω by a small amount before the following scan, where ω is the angle between the incident beam and the wafer surface and 2θ is the angle between the incident beam and the detect. This gives a radial sector of reciprocal space, and can then be converted using software to form a reciprocal space image or "map." The 63.3 MeV proton irradiation was performed at the Crocker Nuclear Laboratory at the University of California at Davis, to fluences as high as 5×10^{13} p/cm^2 (equivalent to 6.8 Mrad(Si) of total ionizing dose) [9].

4. Results

4.1. As-grown samples

Cross-sectional transmission electron microscopy (TEM) was used to measure the thickness of each layer of the stable, metastable, and unstable as-grown samples. Fig. 2 is the TEM images of the stable, metastable, and unstable samples, showing no obvious dislocations at the Si/SiGe interfaces. Carefully calibrated secondary ion mass spectrometry (SIMS) was also used to characterize the layer thicknesses and Ge fraction in the SiGe layers, as shown in Fig. 3. Table 1 gives a summary of the measured thickness and Ge fraction of all the three types of samples by TEM and SIMS, which correlate well with their designed nominal values.