Growth study of surfactant-mediated relaxed SiGe graded layers for 1.55-μm photodetector applications


^aDevice Research Laboratory, Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095, USA
^bDepartment of Materials Science and Mineral Engineering, University of California at Berkeley, Berkeley, CA 94720, USA

Abstract

A systematic study of Sb surfactant-mediated relaxed SiGe graded layers has been performed. The results have been compared with those of relaxed SiGe layers grown at high temperatures, showing that the Sb-mediated SiGe graded layers have been significantly improved both in surface smoothness and in threading dislocation density. We have investigated the grading rate dependence on the resulting threading dislocation density and surface smoothness of as-grown SiGe buffer layer samples. With the use of Sb surfactant mediation, we have also fabricated high-quality Ge photodiodes, showing very low leaky current at the reverse bias at 1 V. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Sb surfactant; SiGe graded buffers; Ge p-i-n photodiodes

1. Introduction

Thin relaxed SiGe buffer layers with a smooth surface and low threading dislocation density are extremely desirable and important for various Si-based optoelectronic applications. Previously, strain-relaxed SiGe buffers were realized by at least three methods. One is to grow compositionally graded SiGe layers at high temperatures (typically at 700–900°C) with a typical grading rate of 10% Ge per 1 μm [1]. The second one is to use a low temperature Si buffer (typically grown below 400°C) on which a SiGe layer of constant composition is grown at approximately 550°C [2]. Another one is to introduce impurities, such as carbon, into SiGe layers to adjust the strain [3]. These techniques have disadvantages of long growth times, thick buffer layers, rough surfaces, high residual strain degree, and/or high threading dislocation densities. Recently, we have reported a significant improvement of the quality of SiGe graded buffer layers by using Sb as a surfactant [4]. In this paper, we have reported in detail the growth of Sb surfactant-mediated relaxed SiGe graded layers. Some results in the application of the Sb surfactant mediation concept for Ge photodiodes will also be discussed.

2. Experimental and results

The growths were carried out using a solid source molecular beam epitaxy system. Si(100) wafers with a resistivity of 1–30 Ωcm were selected as starting materials. All Sb-mediated samples were grown at 510°C with one monolayer Sb deposition before the graded buffer layer growth. As a result, sample A consisted of a 2-μm-thick graded SiGe with a grading rate of 25% Ge per 1 μm, followed by a 0.3-μm constant Si_{0.5}Ge_{0.5} buffer. For comparison, sample B had the same structure as the sample A, except that it was grown at 700°C.
and no Sb pre-deposition was used. All the samples were not intentionally doped, except that the Ge photodiode structures were doped to form p-i-n structures.

Fig. 1 shows typical Raman spectra for samples A and B. The three strong first-order optical lines in each spectrum are due to Ge–Ge (approx. 287 cm⁻¹), Si–Ge (approx. 405 cm⁻¹), and Si–Si (approx. 487 cm⁻¹) atomic vibrations. By using either the frequencies of Si–Si and Si–Ge or the relative intensities between Si–Si and Ge–Ge [5], we obtained the Ge mole fractions in the top constant layers of 0.5 ± 0.01 and 95–100% relaxation for both samples.

The surface morphology difference between samples A and B is apparent. The crosshatch lines of the sample A are long and straight, while those of the sample B are short and somehow kinked, indicating a much higher threading dislocation density in the sample B. The surface root mean square (rms) roughness was estimated to be 20 and 161 Å for samples A and B, respectively.

The threading dislocation densities of the samples were obtained using both TEM and the Schimmel defect etch method [6]. Fig. 3a shows bright field (BF) TEM image of the sample A. The region of the buffer closer to the substrate, approximately 1.5-μm thick, shows high density of misfit and threading dislocations. The dislocation density is higher in the middle of the buffer than that close to the buffer/Si substrate interface. The upper part of the graded buffer and the top constant Si₀.₅Ge₀.₅ layer are almost dislocation-free. Fig. 3b shows the BF image of the sample B. The threading dislocation density in the sample B was determined by counting dislocation ends to be in the range of 10⁹ cm⁻², which is several orders of magnitude higher than that in the sample A. Detailed Schimmel defect etching shows that threading dislocation density in the top constant Si₀.₅Ge₀.₅ layer of the sample A is 1.5 × 10⁴ cm⁻² [4], while the etch pits on the surface of the sample B are too dense to count [7].

Taking into account the optical microscopy resolution limit [8], we obtained the threading dislocation density in the sample B being larger than 10⁹ cm⁻². Thus, the defect etching results are in agreement with the TEM results.

In order to gain more insight of Sb mediation, we have investigated the grading rate dependence on the resulting threading dislocation density and surface roughness. All samples were graded to 50% Ge with a 0.2-μm-thick Si₀.₅Ge₀.₅ layer on top. Fig. 4 shows the threading dislocation density as a function of the grad-

---

1 In our previous presentation [7], we have given a number of 6–7 × 10⁷ cm⁻² for this sample, which should be corrected here.
Fig. 4. Threading dislocation density of Sb-mediated samples as a function of their grading rates. ‘•’ is from [9].

Fig. 5 shows the surface roughness as a function of grading rate. The roughness improves a lot compared with those samples grown at higher temperatures. The surface also becomes smoother for the samples with smaller grading rates.

A Sb-mediated photodiode sample was prepared to test the optoelectronics characteristics. The sample was linearly graded to 100% Ge within a 4-μm SiGe buffer and topped with a 0.9-μm Ge cap. A 0.5-μm-thick n⁺ layer was embedded in the upper graded buffer. The top 0.1-μm-thick Ge layer was doped to form the p⁺ layer with the bottom 0.8-μm-thick Ge acting as intrinsic layer. At the reverse bias of 1 V, we obtained the dark current of the Ge mesa diode of 0.05 mA/cm². Detailed detector performance will be reported elsewhere.

3. Conclusion

Sb surfactant-mediated growth of graded buffer layers has been shown to improve the quality markedly. A graded layer to 50% Ge grown by this method shows a threading dislocation density of $10^4$ cm⁻² and a rms roughness of 20 Å, while a similar sample grown at 700°C has a threading dislocation density in the range of $10^5$ cm⁻² and a rms roughness of 161 Å. Ge p-i-n photodiodes fabricated by this method exhibit very low dark current, indicating Sb surfactant-mediated SiGe graded layers can be very useful in Si-based optoelectronics.

Acknowledgements

This work was in part supported by a US DOD/ONR MURI project on thermoelectrics (Dr John Pazik).

References