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Initial Growth Stages of Si–Ge–Sn Ternary Alloys Grown on Si (100) by Low-Temperature Molecular-Beam Epitaxy

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Abstract—Temperature dependence of the critical thickness of the transition from two-dimensional to three-dimensional growth of the $Ge_{1-5x}Si_{4x}Sn_x$ films grown on Si (100) by molecular-beam epitaxy in the temperature range 150–450°C has been experimentally determined. This dependence is nonmonotonic and is similar to that of the critical thickness for the transition from two-dimensional to three-dimensional growth in the case of the deposition of pure Ge on Si (100) and is caused by a change in the mechanism of two-dimensional growth. Data on the average size and the density of islands, and the ratio between the height of the islands and their lateral size are obtained by the methods of atomic force microscopy and scanning tunneling microscopy. As the growth temperature is increased from 200 to 400°C, the average size of the nanoislands increases from 4.7 to 23.6 nm.

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1. INTRODUCTION

The microelectronic and optoelectronic applications of materials from Group IV of the periodic Table are limited due to a mismatch between the lattice constants of elemental semiconductors Si, Ge, and of their compounds, and also due to a small shift of the conduction band as a result of a variation in the composition in heterojunctions for these materials. Attempts directed at attaining the ability to independently control the band gap and strain caused by differences between the lattice parameters of the film and those of the substrate stimulated efforts toward the development of new semiconductor compounds.

Recently, ternary Si–Ge–Sn solutions have been studied. They feature interesting electronic and transport properties. In particular, independent control of the band gap and the lattice parameter was demonstrated in the family of ternary compounds Si–Ge–Sn, the lattice parameter of which coincides with that of elemental Ge [1, 2]. These data were obtained first for Group-IV semiconductors and made it possible to fabricate new optoelectronic devices compatible with silicon technology and covering the range of applications from communications [3–6] to high-efficiency solar cells [7]. In addition, due to a decrease in the band gap, the optical sensitivity of *p–i–n* photodetectors based on GeSn compounds is increased in comparison with germanium detectors [8]. Some studies have indicated that Si–Ge–Sn compounds can behave as direct-gap semiconductors [9, 10].

Epitaxial growth of $Si_xSn_yGe_{1-x-y}$ semiconductor compounds is complicated by the difference between the lattice constants of Sn and Ge (15%), Sn and Si (19%), by the low equilibrium solubility of Sn in Si and Ge (< 1%), and also by the instability of the diamond-like structure of α-Sn and the tendency to Sn surface segregation [11]. However, using nonequilibrium methods for growth, for example, low-temperature molecular-beam epitaxy (MBE), it is possible to grow single-crystal SiGeSn films with a Sn content as high as 25% [12]. Success in fabricating such compounds becomes possible as a result of the considerable degree of the replacement of Ge and Si atoms with Sn atoms under nonequilibrium conditions at low growth temperatures of 100–350°C.

The lattice constants of diamond-like Si–Ge–Sn alloys are consistent with Vegard's law; therefore, linear interpolation of the lattice constants between Si, Ge, and α-Sn makes it possible to obtain the lattice constant of the $Si_xSn_yGe_{1-x-y}$ ternary solution equal to that of elemental Ge. This circumstance is used in this study in order to investigate the initial stages of growth of $Si_xSn_yGe_{1-x-y}$ ternary alloys with the lattice constant of Ge. Previously, data were obtained on the initial stages of growth of GeSn binary alloys on Si (100) [13]. In this case, the growth of GeSn, as also the growth of pure Ge on Si (100), follows the Stranski–Krastanov mechanism.

In this study, we obtained the growth-temperature dependences for the critical thickness of the 2D–3D transition for $Si_xSn_yGe_{1-x-y}$ ternary alloys with a lat-