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The photoluminescence investigations of mono- and multilayer structures with GeSi/Si(001) self-assembled nanoislands grown at different temperatures.

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1. Introduction

In recent years, an active search has been conducted for ways of integrating opto-electronic devices such as light-emitting diodes, photodetectors and light modulators into modern highly developed Si-based electronics. Therefore $Si_{1-x}Ge_x/Si(100)$ structures with self-assembled islands where the photoluminescence (PL) in the range 1.3 - 1.8 μm was observed are of the great interest. In this work the analysis of PL spectra from SiGe structures with nanoislands grown at different temperatures was performed.

2. Experimental procedure

The samples under investigation were grown by solid-source molecular beam epitaxy on Si (001) substrates. Pure Ge with equivalent thickness varying from 5 to 11MLs was deposited on a Si buffer layer at growth temperatures T_g=600°C, 700°C and 750°C. The multilayer structures were grown at T_g=600°C and T_g=700°C and consist of five Ge layers with equivalent thickness ~ 7.5 ML separated by 300 nm and 600 nm Si space layers respectively. The composition and residual elastic strain (RES) were obtained by X-ray diffraction measurements.

3. Results and discussion

The earlier investigations showed that a significant decrease of Ge content in the islands take place at the growth temperature (T_g) increase from 600⁰C to 750⁰C [2]. The average Ge content (x) in free-standing dome-islands, obtained by X-ray analysis, decreases from about 70÷75% at T_g=600°C to 40÷50% at T_g=750°C. The farther increase of Si content in the islands takes place at high temperature (T > 500°C) overgrowth [3], [4]. X-ray diffraction measurements showed that the island related signal from monolayer structures – structures with one layer of deposited Ge - with Si cap layer is too weak and smear to define the island composition. The dependence of composition of the islands on growth temperature causes a sufficient difference between PL of structures with islands grown at different temperatures (fig. 1). It clearly seen on figure 1 that the maximum of PL peak from the islands grown at T_g=600°C is 60 meV redshifted in comparison with islands formed at T_g=700°C. This redshift is associated with an increase of Ge content in the islands at growth temperature decrease. The main part of PL signal from the islands grown at T_g=600°C is situated at the energies lower than the bulk Ge bandgap (E_g=0.72 eV at 77 K). It was the reason why we used InSb detector instead of commonly used Ge detector with sensitivity more than two order better than sensitivity of InSb detector.

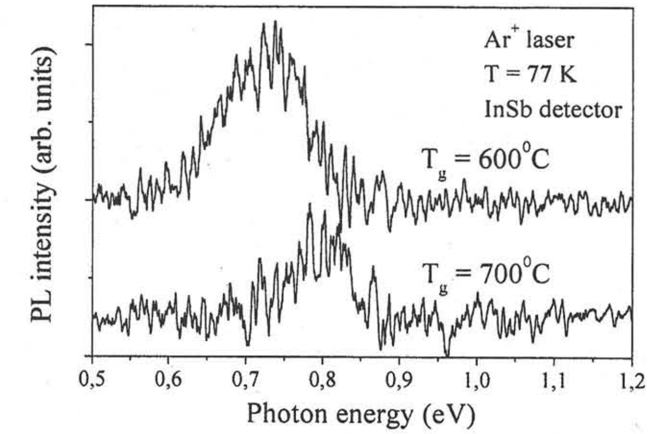

Fig.1 PL spectra of structures with islands grown at T_g=600°C and T_g=700°C. The measurements were carried out at 77 K by InSb detector.

The PL spectra from multilayer structures with islands grown at T_g=600°C and T_g=700°C and measured by InSb detector at 77 K are shown on figure 2. Comparative analysis with monolayer structures showed that 15 – 20 meV redshift takes place for structures grown at T_g=600°C and 15 – 20 meV redshift - for structures grown at T_g=700°C.

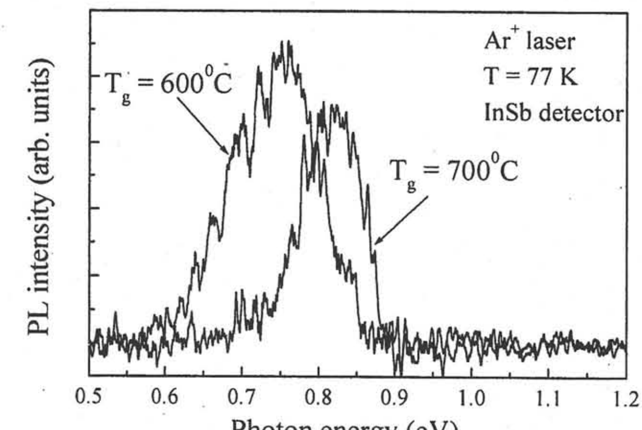

Fig.2 PL spectra of multiplayer structures with islands (five periods) grown at T_g=600°C and T_g=700°C. The measurements were carried out at 77 K by InSb detector.

It can be explained by the decrease of Ge content in the multilayer structure islands because of larger time of growth and therefore time of diffusion of Si atoms into the islands. The X-ray analysis showed that for multiplayer structures grown at T_g=600^{0}C an average Ge content in the islands is x=48%±5%, for multilayer structures grown at T_g=700^{0}C - x=36%±5% and residual elastic strain RES=80±20%. The main part of PL peak from the islands is laying at the energies lower than the bandgap of strained Ge_xSi_{1-x} alloy. This fact confirms that the PL signal from the islands is associated with an indirect optical transition between holes localized in the islands and electrons localized in Si matrix on the heterojunction with islands [1]. The energy of this optical transition was calculated and equals for structures grown at T_g=600^{0}C E = 0.76 eV ± 0.05 eV and for structures grown at T_g=700^{0}C E = 0.86 eV ± 0.04 eV and is in good agreement with an experiment (fig. 2). The width of PL peak from the islands in multilayer structures not less than from the islands in monolayer structures in spite of results of an atomic force microscopy investigations that shows the more uniform island size distribution in the case of multilayer structures. It was observed in reference [5] by transmission electron microscopy that Ge content in the islands depends on bedding depth of layer with islands. The decrease of Ge content takes place with an increase of bedding depth of layer with islands because of larger time of diffusion of Si atoms in the islands at high temperature. The increase of island composition distribution can explain the broad PL peak from the islands in multilayer structures.

The valence band discontinuity on heterojunction Si – island (250 ÷ 350 meV) by one order more than thermal energy of charged carriers at room temperature (25 meV). The hole localization in the islands results in temperature stability of PL signal from the islands. PL signal from the islands was observed up to room temperature (fig. 3). The relation between intensities of PL signal from multi- and monolayer structures increases for samples grown at T_g=600^{0}C from 1.5 to 6 with measurement temperature increase from 77 K to 300 K but for samples grown at T_g=700^{0}C this relation remains the same ~1.5. The relation between intensities of PL signal from the islands of multilayer structures grown at T_g=600^{0}C and T_g=700^{0}C increases from 1.3 to 10 with measurement temperature increase from 77 K to 300 K. It is clearly seen these relations on figure 3, where PL spectra of multi- and monolayer structures with islands measured at room temperature are depicted, though the low-energy shoulder of PL signal from the islands grown at T_g=600^{0}C is slightly cut by Ge detector. The relation between intensities of PL signal from the islands of mono- and multilayer structures grown at T_g=600^{0}C was calculated from spectra measured at room temperature by InSb detector.

We suppose that such behavior of the island related PL shows the weaker localization of charged carriers - electrons in Si on the heterojunction with island - in structures grown at higher temperature. The decrease of Ge content in the islands with an increase of growth temperature results in a decrease of elastic strain and therefore in shallower potential well for electrons in Si on the heterojunction with island. The depth of potential well for electrons is comparable with thermal energy of them at room temperature. The energy position of island related PL peak slightly depends on temperature of measurement. It is associated with compensation of the decrease of bandgap with an increase of temperature by the increase of hole population on exited levels in the islands. Light-emitting recombination of holes from these levels results in slight dependence of island related PL peak.

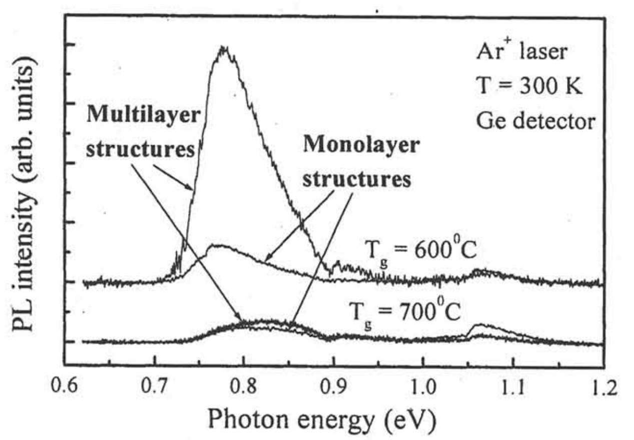

Fig. 3 PL spectra of mono- and multiplayer structures with islands grown at 600^{0}C and 700^{0}C. All spectra were measured at 300 K by Ge detector.

4. Summary

The investigations of PL spectra of mono- and multiplayer structures with nanoislands grown at different temperatures were performed. The redshift of the island related PL peak with a decrease of growth temperature was observed. This redshift is associated with suppression of Si diffusion in the islands and an increase of Ge content in them. PL signal from the islands grown at 600^{0}C was observed at the energies lower than the bulk Ge bandgap. The energy position of island related PL peak is well described by the model of indirect in real space optical transition taking into account the real composition and elastic strain. The structures with GeSi/Si(001) self-assembled nanoislands were obtained having the PL signal from the islands at 1.55 μm up to room temperature. The different behavior of temperature dependence of relation between intensities of PL signal from multi- and monolayer structures was shown.

Acknowledgments

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