Photoluminescence in Three-Dimensional $Si/Si_{1-x}Ge_x$ Nanostructures

B. V. Kamenev[1], L. Tsybeskov[1], J.-M. Baribeau[2] and D. J. Lockwood[2]

[1]Department of Electrical and Computer Engineering, New Jersey Institute of Technology, University Heights, Newark, NJ 07102, USA
[2]Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, ON K1A 0R6, Canada

In Si/Ge, a three-dimensional (3D) growth mode known also as Stranski-Krastanov (S-K) growth results in partially ordered 3D nanostructures with SiGe clusters embedded within a Si matrix. The clustering of SiGe during epitaxial growth is, at least in part, a self-controlled phenomenon, and it is driven by kinetic and thermodynamic processes. Therefore, by varying the preparation conditions, e.g., Ge content, controllable fluctuations of SiGe composition within nanometer size SiGe clusters can be produced. It is important to understand how to control such fluctuations, to fabricate better quality SiGe nanostructures, and to provide favorable conditions for radiative carrier recombination.

The samples used in this study were grown by molecular beam epitaxy under conditions of near S-K growth mode in a VG Semicon V80 system. The structures consist of $Si_{1-x}Ge_x/Si$ multiple quantum wells with different layer thicknesses (t), Ge composition (x) and number of periods (N). Sample details are provided in Table I. Transmission electron microscopy has shown that Si/Ge multilayers with high Ge content (>0.3) grown above 600°C exhibit a SiGe island morphology embedded into a silicon matrix.

Table I. Sample characteristics (layer thickness t, alloy composition x, and number of periods N) and their growth conditions (growth temperature T and growth rates for Si and Ge).

Sample	t_{Si} (nm)	t_{SiGe} (nm)	x	N	T (°C)	Si (nm/s)	Ge (nm/s)
A	27	4	0.09	20	595	0.2	0.05
B	34	7	0.16	15	595	0.2	0.05
C	15	3.5	0.53	10	625	0.1	0.05

We present here detailed photoluminescence (PL) and Raman investigations of these 3D $Si/Si_{1-x}Ge_x$ nanostructures. Using Raman scattering as a major characterization tool, we observed a clear correlation between the Raman signal related to Ge–Ge and Si–Ge vibrations and important PL properties such as the PL peak position, the activation energy of PL thermal quenching, and the PL quantum efficiency. This can be seen in Figs. 1 and 2. In particular, with increasing x, we found that an increase in the Ge-Ge vibration Raman signal clearly correlated with (i) a red shift in the PL peak position, (ii) an increase in the activation energy of PL thermal quenching, and (iii) an increase in the PL quantum efficiency. Time-resolved PL measurements reveal a stretched-exponential long-lived PL component that is associated with compositional and dimensional fluctuations in the SiGe dots.

From our data we conclude that ~ 50% of Ge contained within such Si/SiGe nanostructures is enough Ge to achieve nearly pure Ge segregation within SiGe nanoclusters, i.e., Ge atoms form nanometer size clusters with a nearly pure Ge core that is essentially surrounded by a SiGe shell. Such nanoclusters produce a bright PL at temperatures extending almost up to room temperature. Our work suggests that better control over Ge segregation in 3D Si/SiGe nanostructures may result in new optoelectronic devices compatible with CMOS technology.

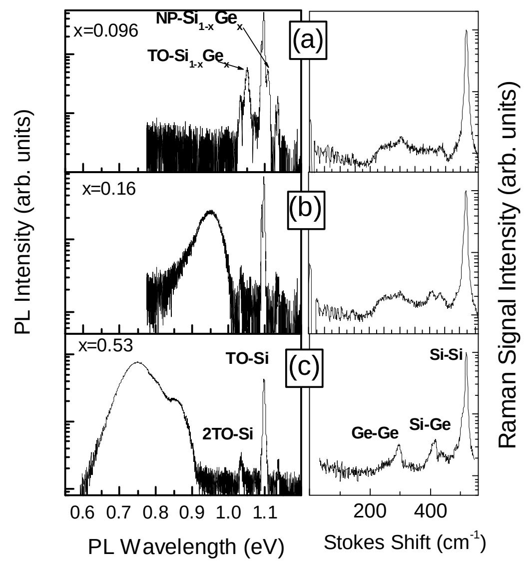

Figure 1. Photoluminescence (left part) and Raman (right part) spectra in 3D $Si/Si_{1-x}Ge_x$ nanostructures of different Ge content: (a) x=0.096; (b) x=0.16; (c) x=0.53. Note the vertical logarithmic scale for both left and right parts.

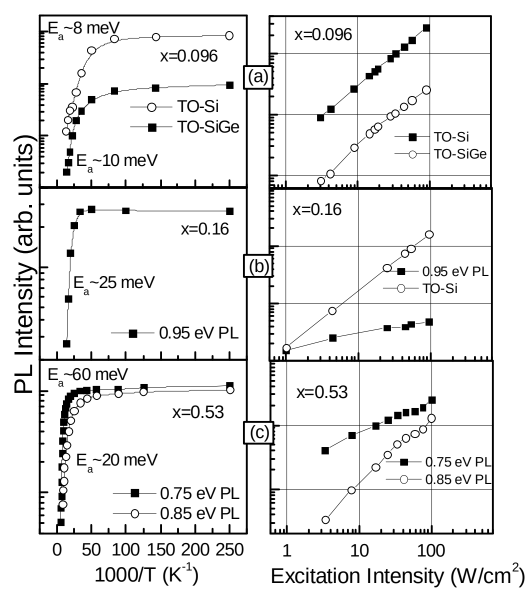

Figure 2. Photoluminescence intensity temperature dependence (left part) and excitation intensity dependence (right part) in 3D $Si/Si_{1-x}Ge_x$ nanostructures of different Ge content: (a) x=0.096; (b) x=0.16; (c) x=0.53. The temperature dependence was measured with an excitation intensity of 3 W/cm^2 and the excitation dependence was obtained at 4 K. (The points are the experimental data and all lines are guides for the eye).